

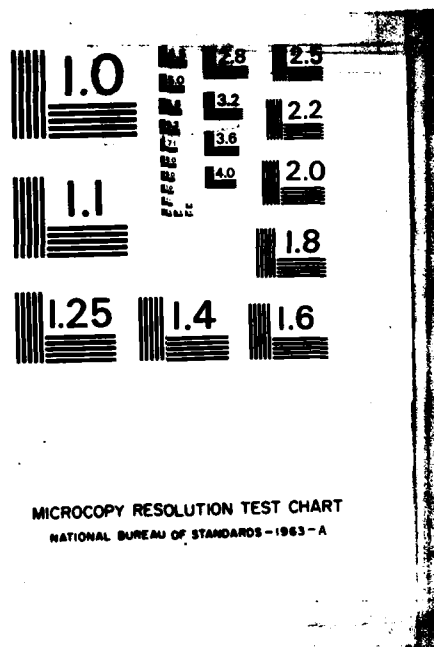
THE CENSORED MEAN-LEVEL DETECTOR FOR MULTIPLE TARGET  
ENVIRONMENTS(U) ORINCON CORP LA JOLLA CA J A PRESLEY  
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## Contractor Report 228

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# THE CENSORED MEAN-LEVEL DETECTOR FOR MULTIPLE TARGET ENVIRONMENTS

J. A. Presley  
ORINCON Corporation  
Contract number N66001-83-C-0324

March 1984  
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Code 62R13

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The contracting officer's technical representative was G. M. Dillard, Associate for Systems, Code 7301, Naval Ocean Systems Center, San Diego, CA 92152, Tel. (619)225-7932.

Released by  
G. M. Dillard, Associate  
for Systems

Under authority of  
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## TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1.0 INTRODUCTION . . . . .	1
2.0 THE CENSORED MEAN-LEVEL DETECTOR. . . . .	3
2.1 The Censor-Before-Averaging CMLD . . . . .	3
2.2 Performance Results for the CBA-CMLD . . . . .	7
2.3 The Two-Pass CBA-CMLD . . . . .	41
2.4 Performance Results for the Two-Pass CBA-CMLD . . . . .	49
2.5 The Censor-After-Averaging CMLD . . . . .	59
2.6 Performance Results for the CBA-CMLD . . . . .	61
3.0 CONCLUSIONS . . . . .	78
4.0 REFERENCES . . . . .	79



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## 1.0 INTRODUCTION

This report presents performance results for a class of robust, constant false alarm rate (CFAR) detectors known as censored mean-level detectors (CMLD). The CMLD, a special case of which is the mean-level detector (or cell-averaged CFAR detector), is an energy detector designed to detect stationary Gaussian signals in stationary, locally homogenous Gaussian noise (Swerling Case II). Solutions to this classical problem have found applications in many diverse fields and performance results for the CMLD in passive sonar applications can be found in Reference [1], but this report will concentrate on the application of the CMLD to the radar detection problem.

The mean-level detector (MLD) is the generalized maximum likelihood detector for this application [2], and it obtains its noise power estimate as an average of the power in neighboring (in range/Doppler) cells. Previous results have shown [3] that the MLD works very well when the power estimate is uncontaminated by other signals (interferers). However, in many important practical cases, the presence of multiple, closely spaced signals (interferers) will result in a contamination of the noise power estimate that seriously degrades the performance of the MLD [3]. This degradation appears as a severe masking (reduction in probability of detection) of the signal when an interferer is present in the samples used to estimate the noise power.

In an effort to develop a detector having robust performance in multiple target environments, Rickard and Dillard [3,4] investigated a modified MLD that used an average of all but the first, or first and second, largest noise reference samples (i.e., they censored the largest or the first and second largest samples from the average). Their work corresponded to the problem of detection without time averaging. Their results proved that the CMLD [this author's terminology] has important robustness properties that give it performance greatly superior to the MLD in multiple target environments.

In this report these results are extended to include an arbitrary censoring pattern and arbitrary time averaging in the detection process.



## 2.0 THE CENSORED MEAN-LEVEL DETECTOR

The censored mean-level detector (CMLD) is a generalization of the traditional mean-level detector (MLD) or cell-averaged CFAR detector which includes a modification to provide robust performance in multiple target environments by including censoring of selected order statistics from the noise power estimate. As in the MLD, the CMLD obtains its noise reference pool from neighboring (in range/Doppler) resolution cells. This report will consider a CMLD implementation where the input data is the detected power versus range; but an implementation including a Doppler dimension could be easily handled by a change in the indexing schemes.

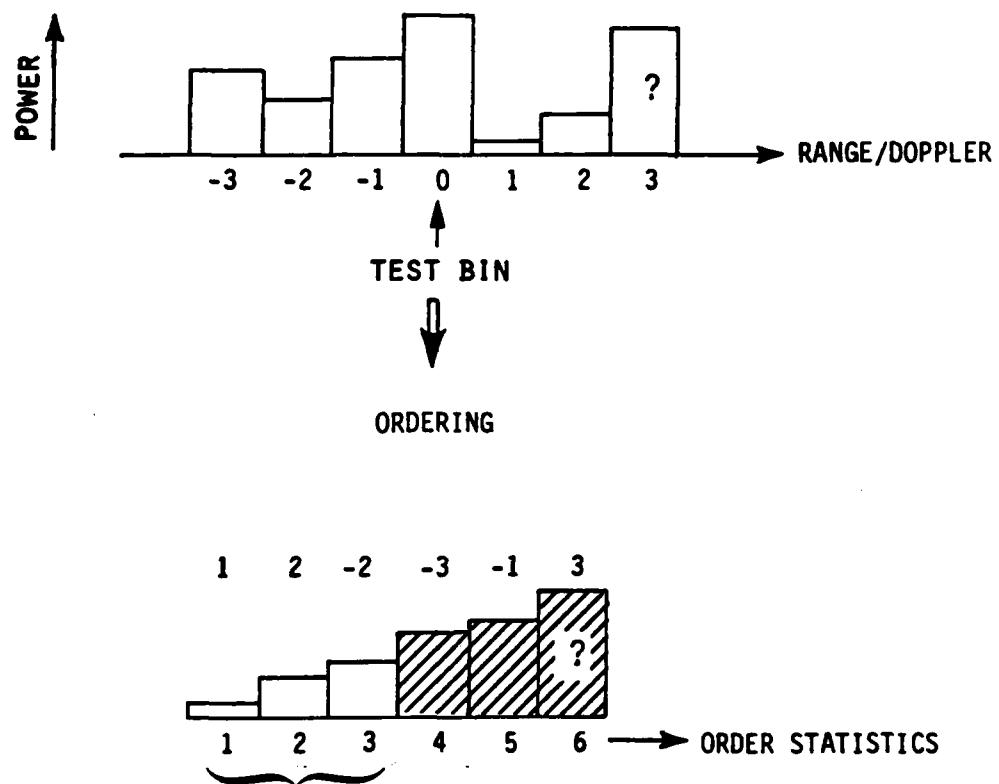
In Figure 1, a simple example of the process used to form the censored mean is given where the locally obtained noise reference pool may contain an interfering target (bin 3). Even so, the censored mean,  $W$ , does not contain the contaminated sample (order statistic 6). Three classes of CMLD will be considered in this report:

1. Censor-Before-Averaging (CBA) CMLD;
2. Two-Pass CBA-CMLD; and
3. Censor-After-Averaging (CAA) CMLD.

### 2.1 The Censor-Before-Averaging CMLD

In the CBA-CMLD, a vector of censored means is produced for each return vector of power versus range. Then any desired amount of time averaging (over returns) of the censored means is used to form the final noise power estimate.

We start all of the CMLD processes with a vector of power versus range,  $R(j,k)$ , at a time,  $k$ , for range,  $j$ . The underlying assumption on  $R$  is that the complex sample whose magnitude squared value is  $R$  was drawn from a set of zero-mean, independent, identically distributed Gaussian random variables when no signals or interferers are present (under  $H_0$ ). Additionally, when present, the signals



THESE BINS ARE AVERAGED TO  
FORM THE BIASED NOISE POWER  
ESTIMATE,  $W$

Figure 1. The censored mean-level detector.

or interferers (under  $H_1$ ) are also zero-mean, independent Gaussian random variables with different variances (Swerling Cases II).

First, an estimate in the form of a time average over  $N$  samples,  $S(j)$ , is made of the power in each of the test bins as follows:

$$S(j) = \frac{1}{N} \sum_{k=1}^N R(j,k) . \quad (1)$$

Then, for each return and each range a local noise reference pool is defined as the  $M$ -element set:

$$U(j,k) = \{R(n,k)\}_{n=j - \frac{M}{2}, j + \frac{M}{2}} . \quad (2)$$

Then, for time,  $k$ , and range,  $j$ , the set  $U(j,k)$  is ordered in increasing power and the ordered elements of  $U$ , the order statistics, are labeled  $Y(n,j,k)$  where  $n$  ranging from 1 to  $M$  is the rank of the corresponding order statistic. The order statistics have the following property:

$$0 \leq Y(1,j,k) \leq Y(2,j,k) \cdots \leq Y(M,j,k) . \quad (3)$$

The biased noise power estimate,  $W(j)$ , is then formed as:

$$W(j) = \frac{1}{N} \sum_{k=1}^N \frac{1}{M-a-b} \sum_{n=b+1}^{M-a} Y(n,j,k) , \quad (4)$$

where at each time (return) the  $a$  largest and  $b$  smallest noise reference samples are censored from the average. The censored mean,  $Z(j)$ , is then formed by removing the bias of  $W(j)$ :

$$Z(j) = \frac{W(j)}{E[W]} , \quad (5)$$

where the  $E[W]$ , for a unit power input random process, is obtained analytically as a function of  $M$ ,  $a$ , and  $b$ . The detection statistic is then formed as:

$$D(j) = \frac{S(j)}{Z(j)} \geq T, \quad (6)$$

and since the CMLD is a CFAR statistic, the threshold,  $T$ , is only a function of  $N$ , the number of time samples averaged;  $M$ , the number of noise reference samples per test sample;  $a$ , the number of order statistics censored from above;  $b$ , the number of order statistics censored from below; and the desired probability of false-alarm. The threshold values for the CBA-CMLD are obtained from exact analytical expressions for the probability of detection and false-alarm of the CMLD.

Several special members of the class of CMLDs are interesting cases. First, when  $M-a-b$  approaches infinity, the CMLD approaches the optimal energy detector. Second, when  $a=b=0$ , the CMLD reduces to the MLD. Last, when  $a=b=(M-1)/2$  (where  $M$  is odd), the CMLD uses a time average of the sample medians of the noise reference samples as a noise power estimate. This case is the classical median detector.

While CMLD with censoring from below ( $b \neq 0$ ) may well be useful in reducing bias problems when the noise has a slope, this report is primarily concerned with detection robustness in multiple target environments and will, therefore, concentrate on CMLDs where  $b=0$  and  $a \neq 0$ ; since, when an interferer is present in the noise reference samples, that sample is expected to have a high power.

Analytical results do not as yet exist for the performance of the CMLD in arbitrary interference environments, but analytical results do exist for an arbitrary number of discrete interferers with "large" (i.e., infinite) interference-to-noise power ratios (INR). Strictly speaking, the interferers must be censored with-probability-one solely on the basis of their large interference power components. In this

case a CMLD which uses  $M$  noise reference cells and censors the  $a$  largest samples will have a distribution in the presence of  $K$  large discrete interferers identical to a CMLD using  $(M-K)$  noise reference cells and censoring the  $(a-K)$  largest samples (for  $K \leq a$ ). This result gives a worst case, upper bound on the performance degradation of the CMLD caused by the presence of  $K$  discrete interferers for any INR.

In addition, we note that when the CMLD is used to search for targets over a large number of adjacent bins, efficient merge-sorting techniques can greatly reduce the computational loading over that of ordering with a full sort for each test bin.

## 2.2 Performance Results for the CBA-CMLD

The performance comparisons in this report will be based on the signal-to-noise power ratios (SNR) needed to achieve a probability of detection of one-half with a probability of false-alarm of  $10^{-4}$  (under  $H_0$ ). This SNR is the well-known "minimum detectable signal" (MDS) for detection in the presence of white noise (under  $H_0$ ). This SNR will be expressed as the excess signal-to-noise power ratio (EXS); that is, the SNR needed in addition to the MDS for the specified reference detector in order to produce a probability of detection of one-half. For detection in the presence of white noise (under  $H_0$ ), the reference detector will be the corresponding optimal energy detector for the specified amount of time averaging, and the EXS will then be the CFAR loss of the detector in question. For cases including interferers, the performance results will be given for two reference detectors. First, the EXS will be given referenced to the corresponding optimal energy detector, in which case the EXS is a measure of the total performance loss, both CFAR and that due to the presence of interference, for the specified detector in the specified interference environment. Also, the EXS will be given referenced to the MDS (under  $H_0$ ) of the corresponding CMLD (i.e., the same  $N$ ,  $M$ ,  $a$ , and  $b$ ); in this case, the EXS is a measure of the performance loss of the specified detector in the specified interference environment.

Figures 2 through 17 present the performance results for the CBA-CMLD both in the presence of white noise alone (under  $H_0$ ) and in the presence of white noise plus one, two, or three "large" discrete interferers. The results are shown for the following range of parameters: a probability of false-alarm of  $10^{-4}$ ; 1, 2, 4, or 8 time averages (N); 8, 16, 32, or 64 noise reference cells per test cell (M); 0 to (M-1) of the largest samples censored from the noise power estimate (a); and 0, 1, 2, or 3 "large interferers present in the noise reference window (NI). The number of largest noise samples censored is expressed as the "fractional number censored," (a/M).

In the figures marked "a," the reference detector is the optimal (parametric) energy detector for the specified amount of time averaging (N), and the reference MDS is given on the figure as  $MDS_p$  in dB. The lower curve (NI=0) in these figures is the performance under  $H_0$  where the EXS is what is usually called the CFAR loss. The other curves (NI  $\neq$  0) give the total performance loss in the presence of the indicated number of large interferers.

In the figures marked "b," the reference detector is the corresponding (in N, M, a, and b) CMLD (NI=0 in the corresponding figure marked "a"). This figure presents the same data as in the curves, NI = 1, 2, and 3 in the corresponding figure marked "a." The change in reference in the figures marked "b" makes it easier to see the portion of the performance loss attributed to the presence of NI distinct, "large" interferers.

As indicated in these figures,<sup>1</sup> the CMLD has robust performance even in the presence of "large" interferers. There is an obvious trade-off between the additional CFAR loss due to censoring more and the enhanced robustness that this censoring adds. For most cases of

<sup>1</sup>In these calculations, a search for the SNR giving a probability of detection of one-half with not more than a 0.5% relative error in probability was used. This results in SNR with a 0.01 dB or less error which is the source of the minor ripples in some curves.

# EXCESS SIGNAL NEEDED TO OBTAIN $PD = .5$

$PFA = 10^{-4}$   
 $MDS_P = 10.90$

$N = 1$   
 $M = 8$

▲  $NI = 0$   
 ○  $NI = 1$   
 ▼  $NI = 2$   
 □  $NI = 3$

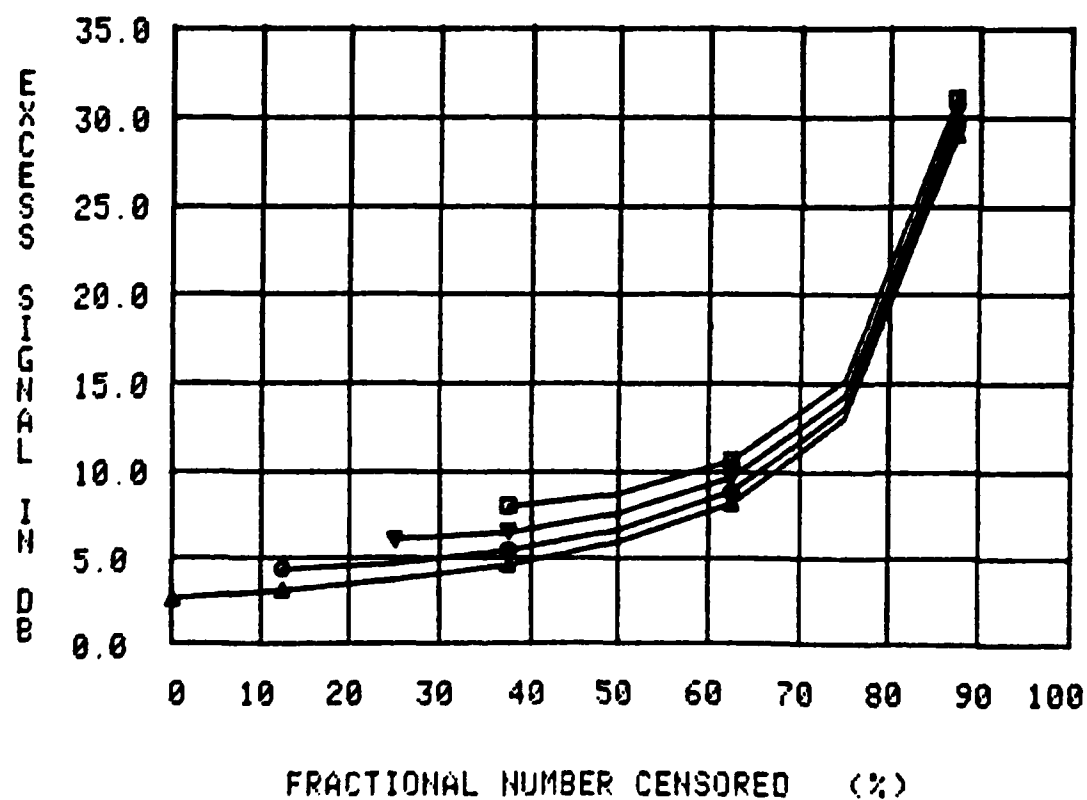


Figure 2a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 1

M = 8

○ NI = 1  
▼ NI = 2  
□ NI = 3

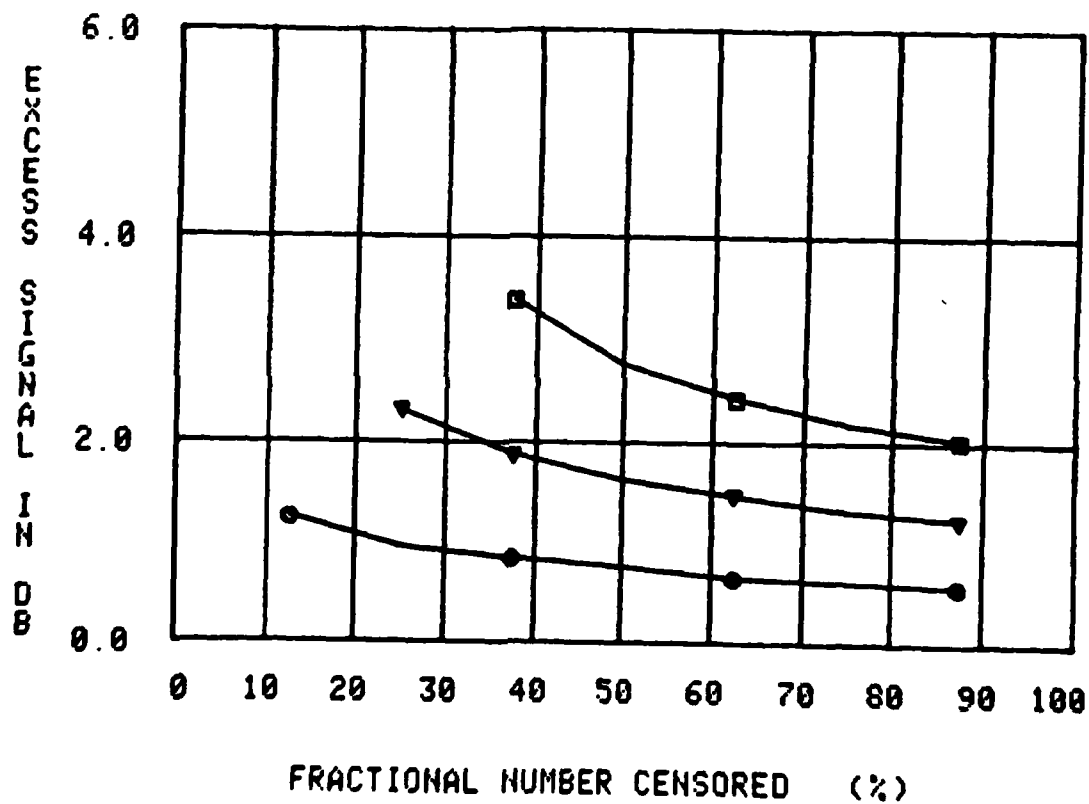


Figure 2b.



# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$   
MDS<sub>P</sub> = 10.90

N = 1  
M = 16

▲ NI = 0  
○ NI = 1  
▼ NI = 2  
□ NI = 3

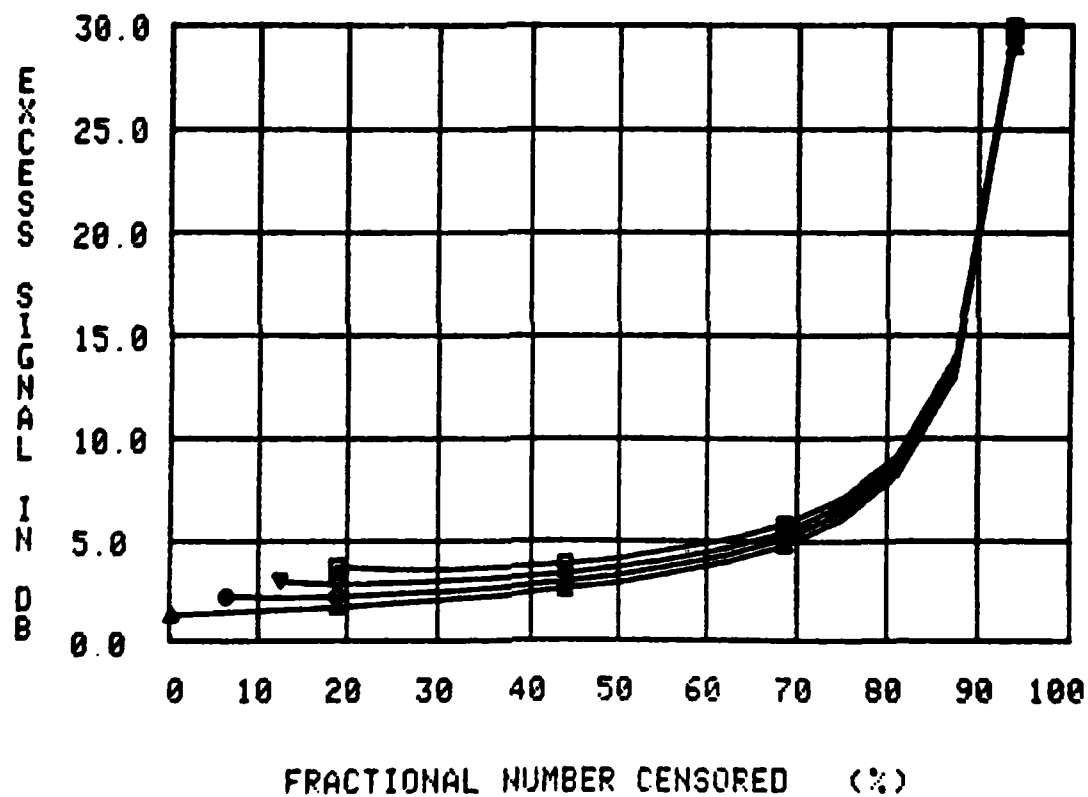


Figure 3a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 1

M = 16

○ NI = 1  
▼ NI = 2  
□ NI = 3

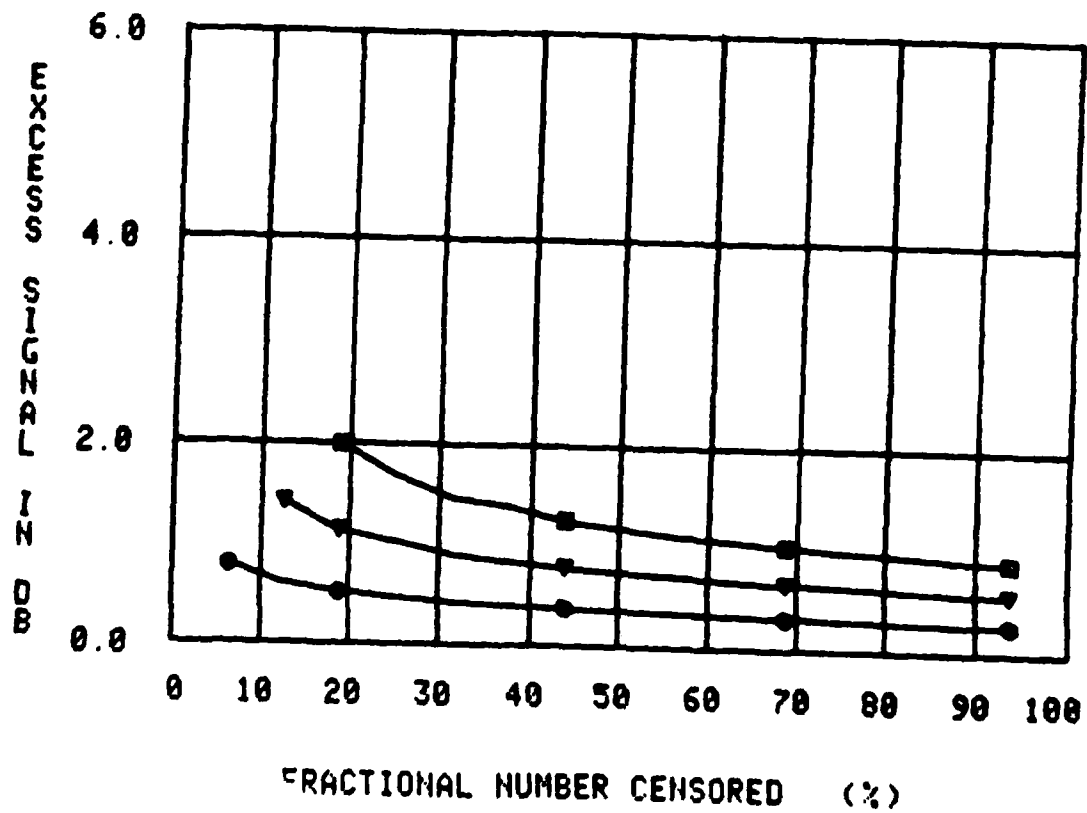


Figure 3b.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$   
MDS<sub>P</sub> = 10.90

N = 1  
M = 32

▲ NI = 0  
○ NI = 1  
▼ NI = 2  
□ NI = 3

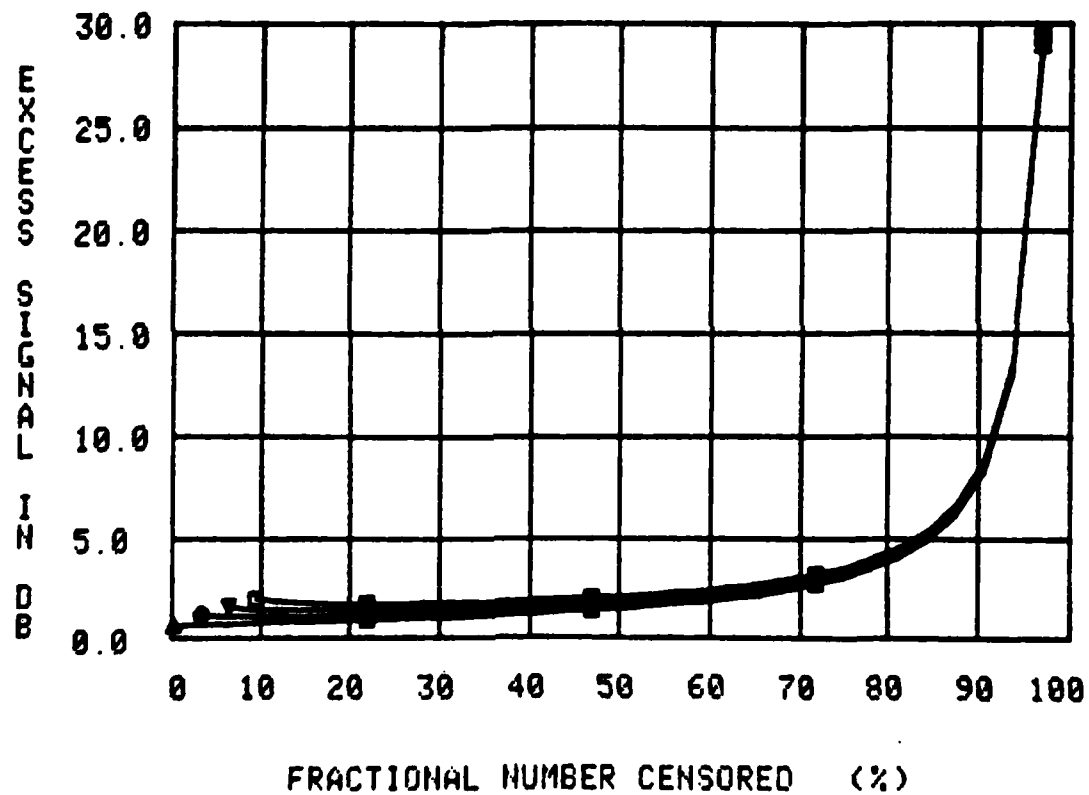


Figure 4a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 1

M = 32

○ NI = 1  
▼ NI = 2  
□ NI = 3

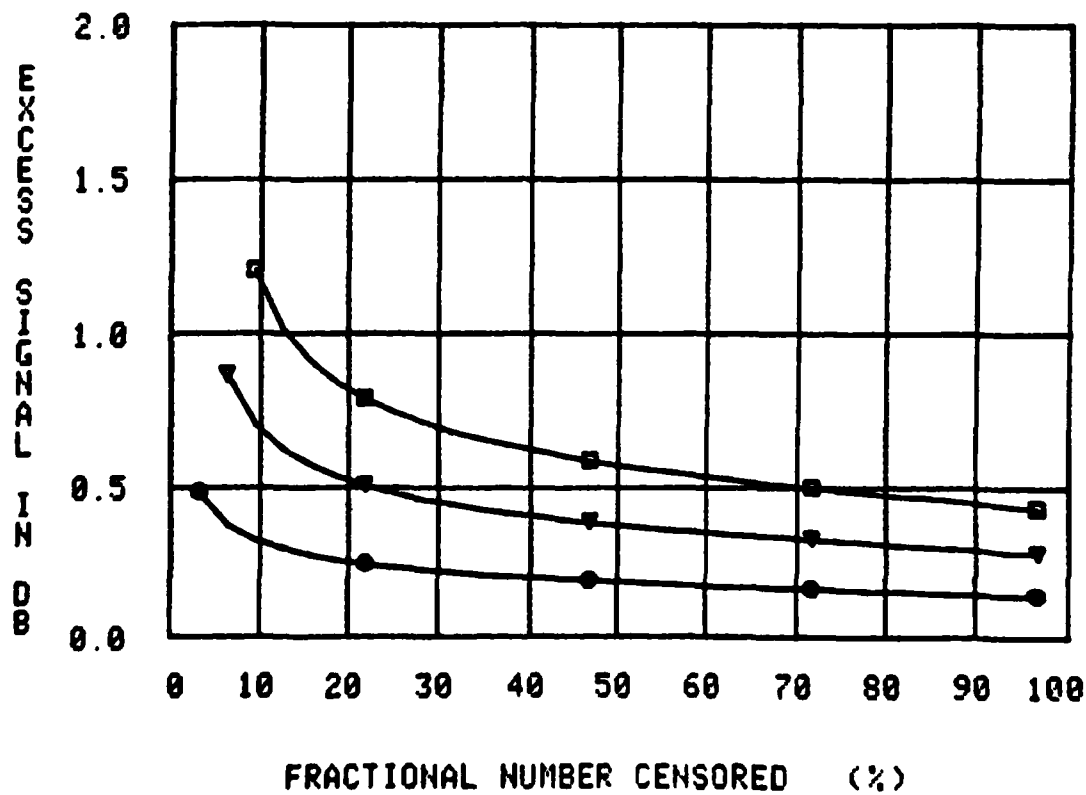


Figure 4b.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$   
MDS<sub>P</sub> = 10.90

N = 1  
M = 64

▲ NI = 0  
○ NI = 1  
▼ NI = 2  
□ NI = 3

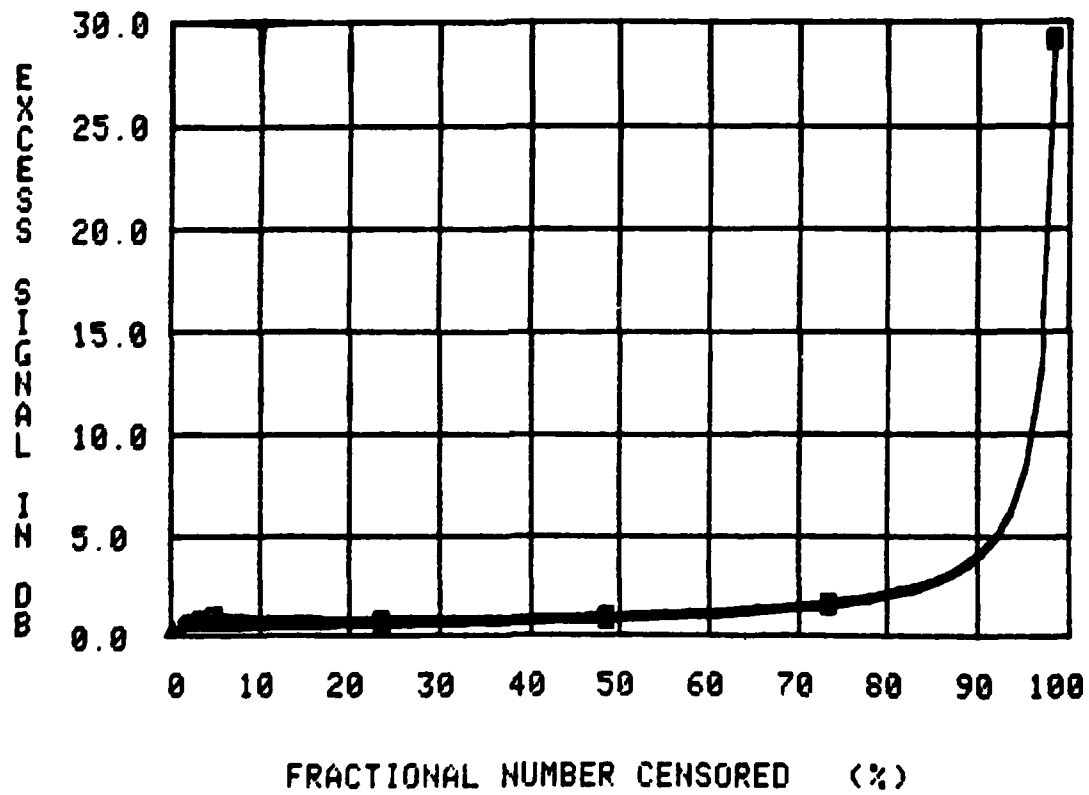


Figure 5a.

EXCESS SIGNAL NEEDED TO OBTAIN  $PD = .5$   
RE MDS FOR CMLD

$PFA = 10^{-4}$

$N = 1$

$M = 64$

○  $NI = 1$   
▼  $NI = 2$   
□  $NI = 3$

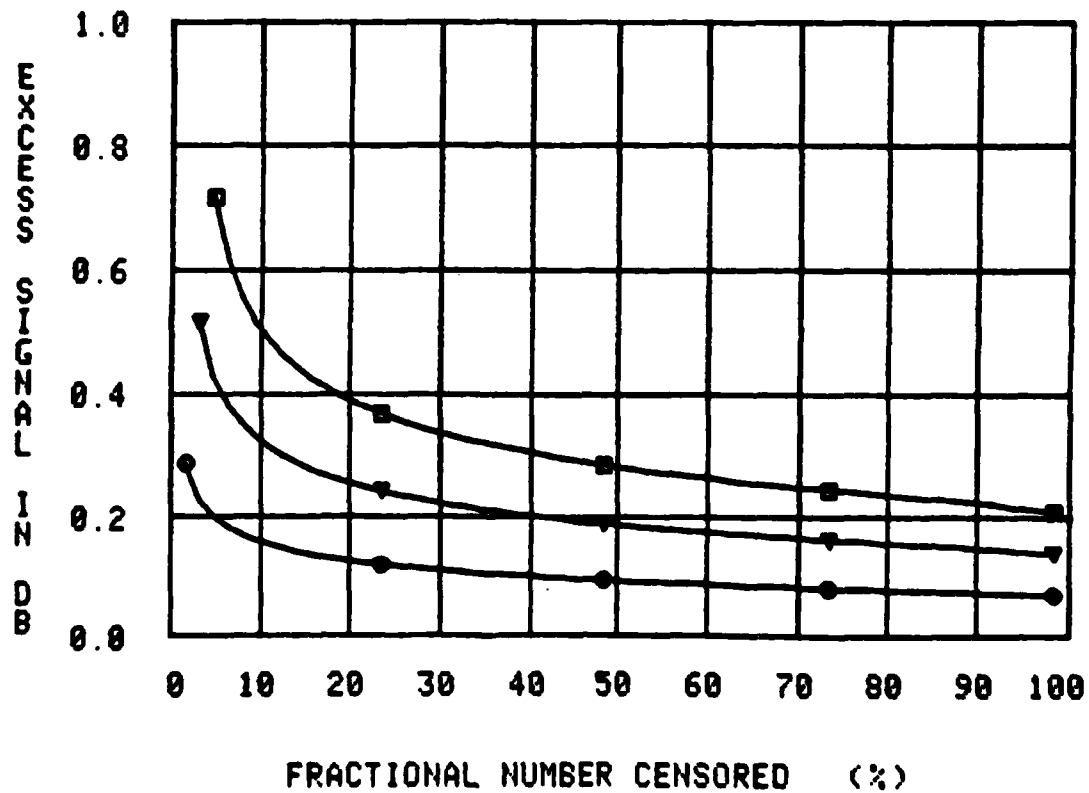


Figure 5b.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$   
MDS<sub>P</sub> = 7.78

N = 2  
M = 8

▲ NI = 0  
○ NI = 1  
▼ NI = 2  
□ NI = 3

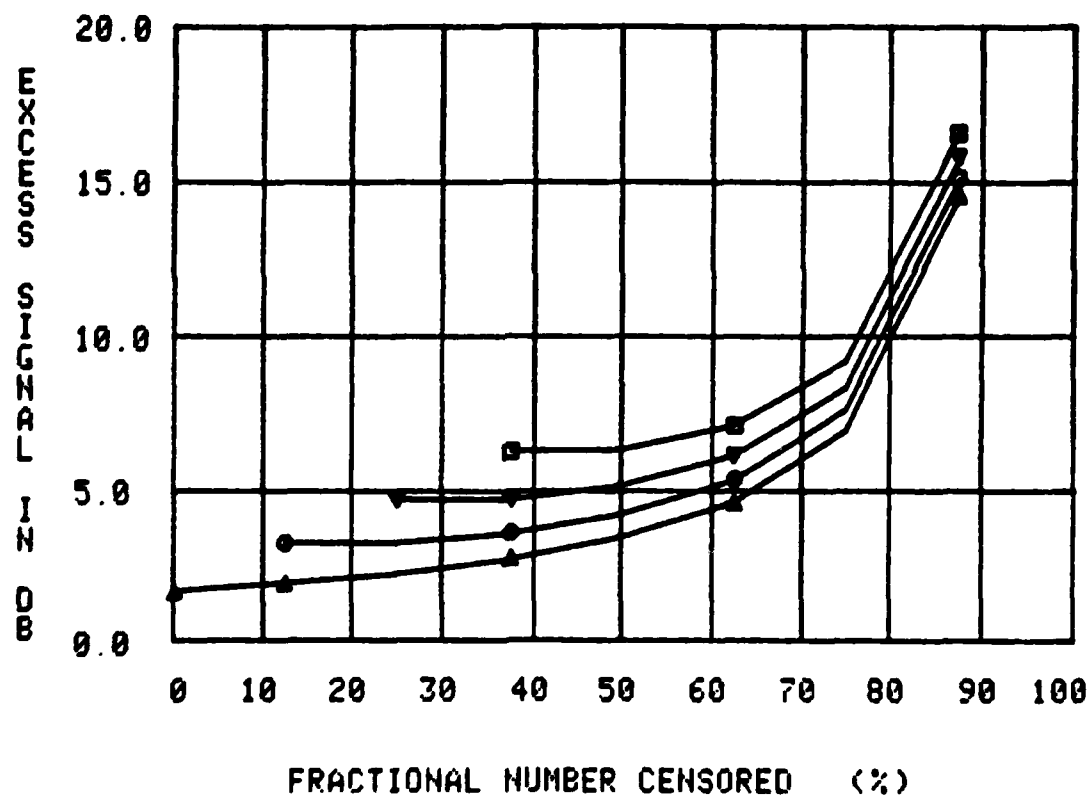


Figure 6a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 2

M = 8

○ NI = 1  
▼ NI = 2  
□ NI = 3

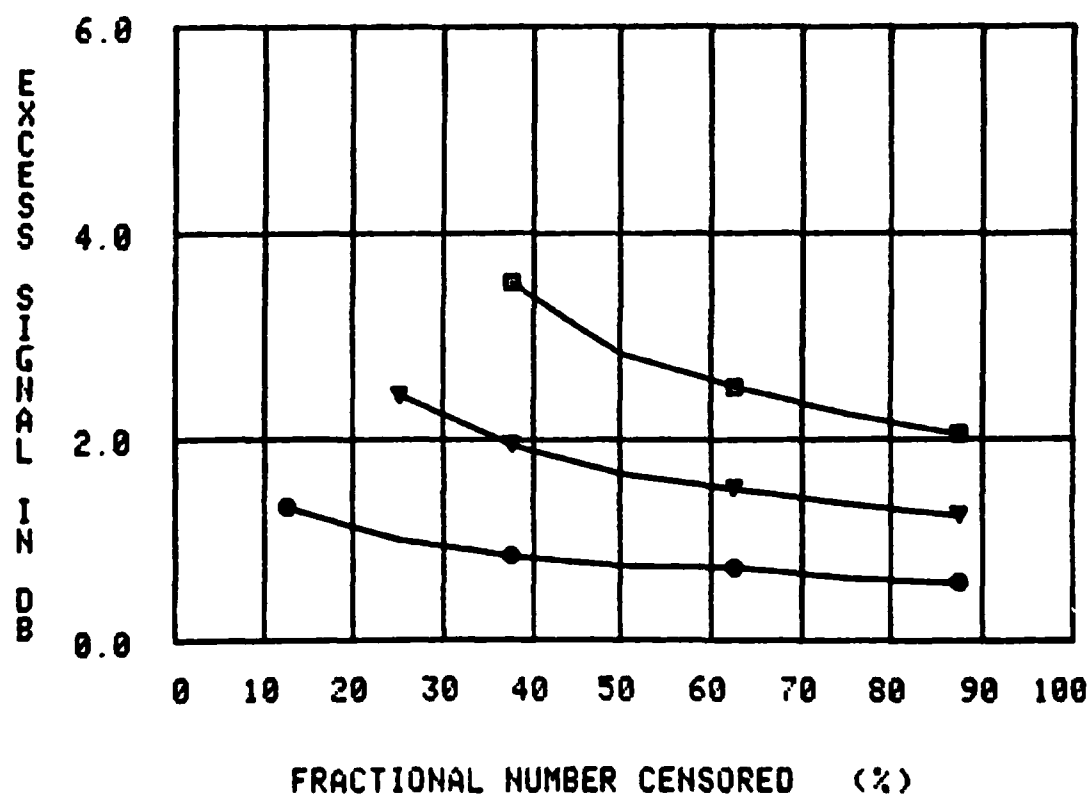


Figure 6b.



# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$   
MDS<sub>P</sub> = 7.78

N = 2  
M = 16

▲ NI = 0  
○ NI = 1  
▼ NI = 2  
■ NI = 3

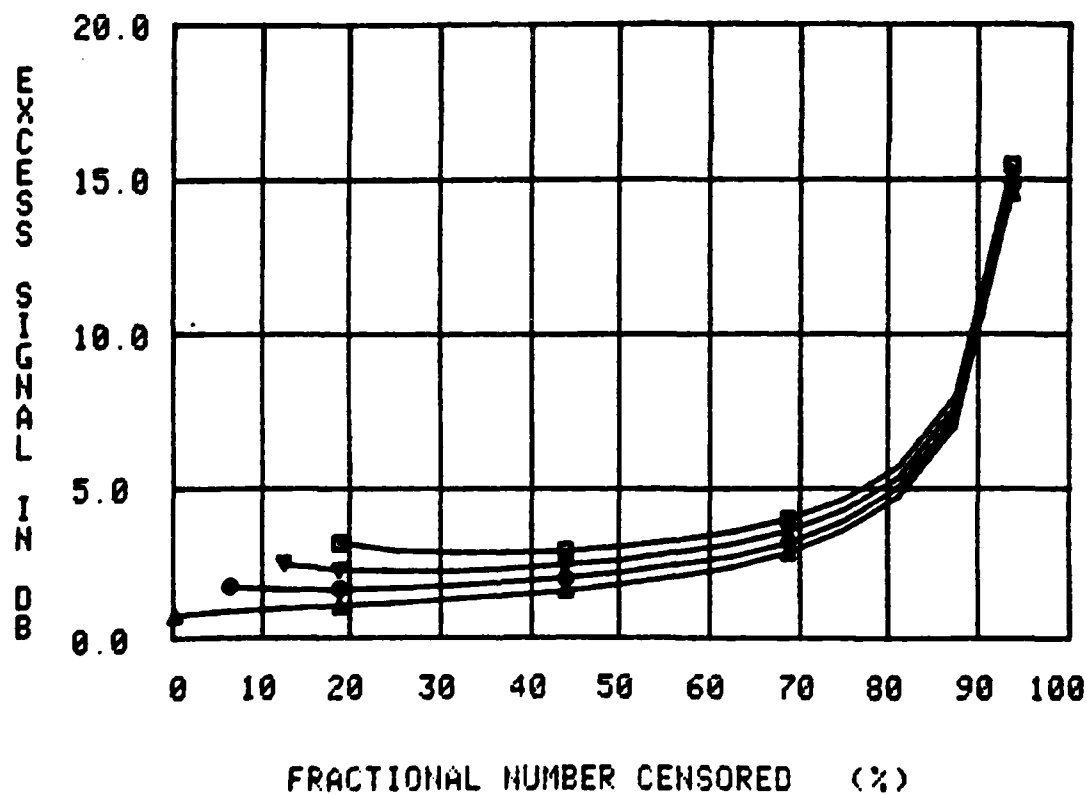
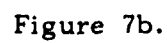


Figure 7a.

PFA =  $10^{-4}$       N = 2      M = 16       $\begin{matrix} \circ & NI & = & 1 \\ \nabla & NI & = & 2 \\ \square & NI & = & 3 \end{matrix}$



# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

$PFA = 10^{-4}$   
 $MDS_p = 7.78$

$N = 2$   
 $M = 32$

▲ NI = 0  
 ○ NI = 1  
 ▼ NI = 2  
 □ NI = 3

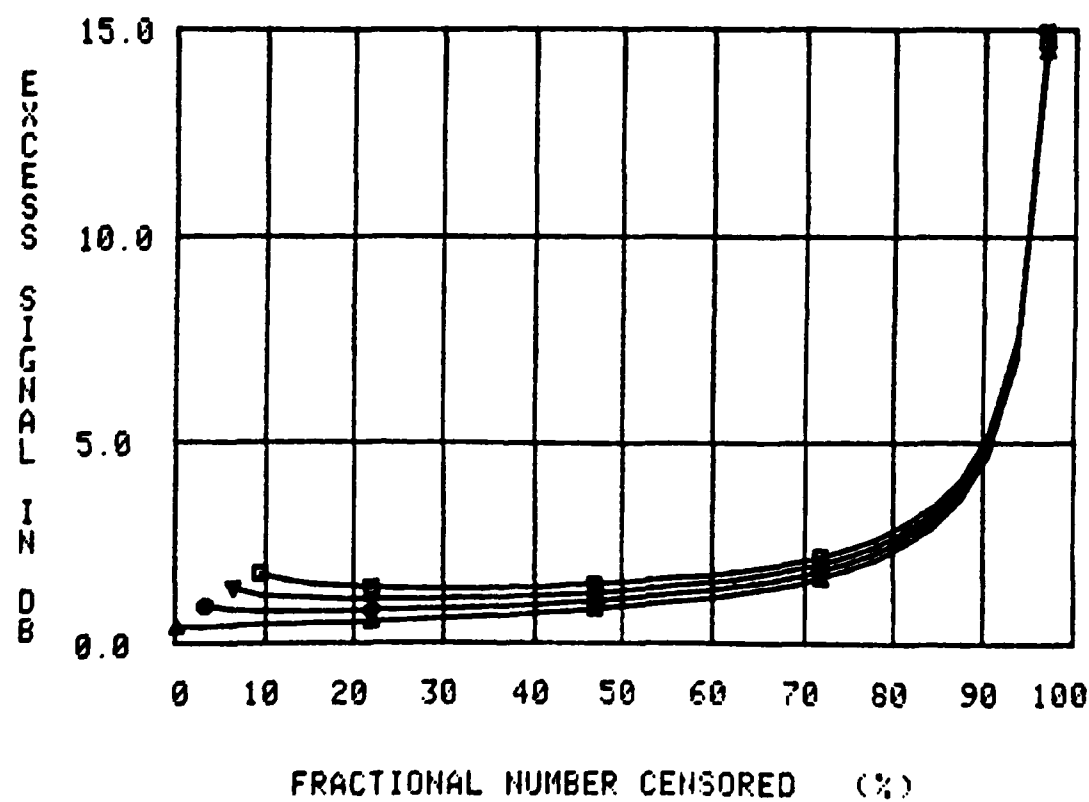
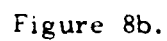


Figure 8a.

PFA =  $10^{-4}$       N = 2      M = 32      NI = 1  
NI = 2  
NI = 3



# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

FFA =  $10^{-4}$

N = 2

▲ NI = 0

MDS = 7.78  
P

M = 64

○ NI = 1

▼ NI = 2

□ NI = 3

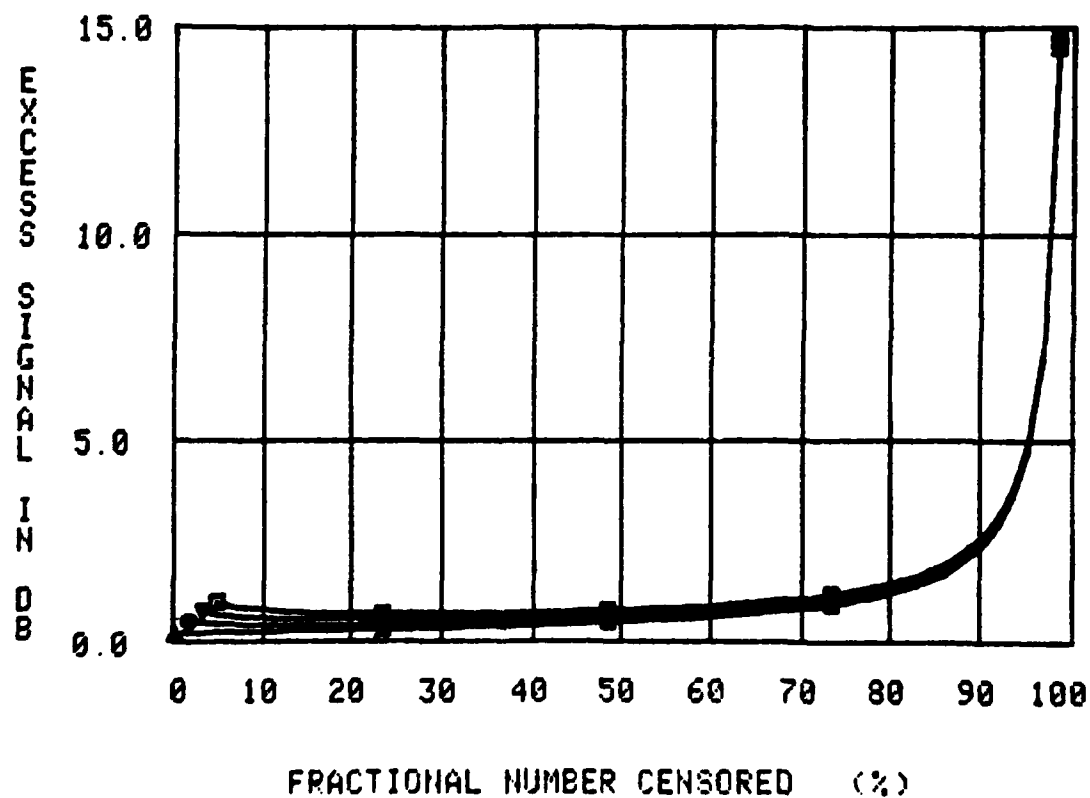


Figure 9a.

EXCESS SIGNAL NEEDED TO OBTAIN  $PD = .5$   
RE MDS FOR CMLD

$PFA = 10^{-4}$

$N = 2$

$M = 64$

○  $NI = 1$   
▼  $NI = 2$   
□  $NI = 3$

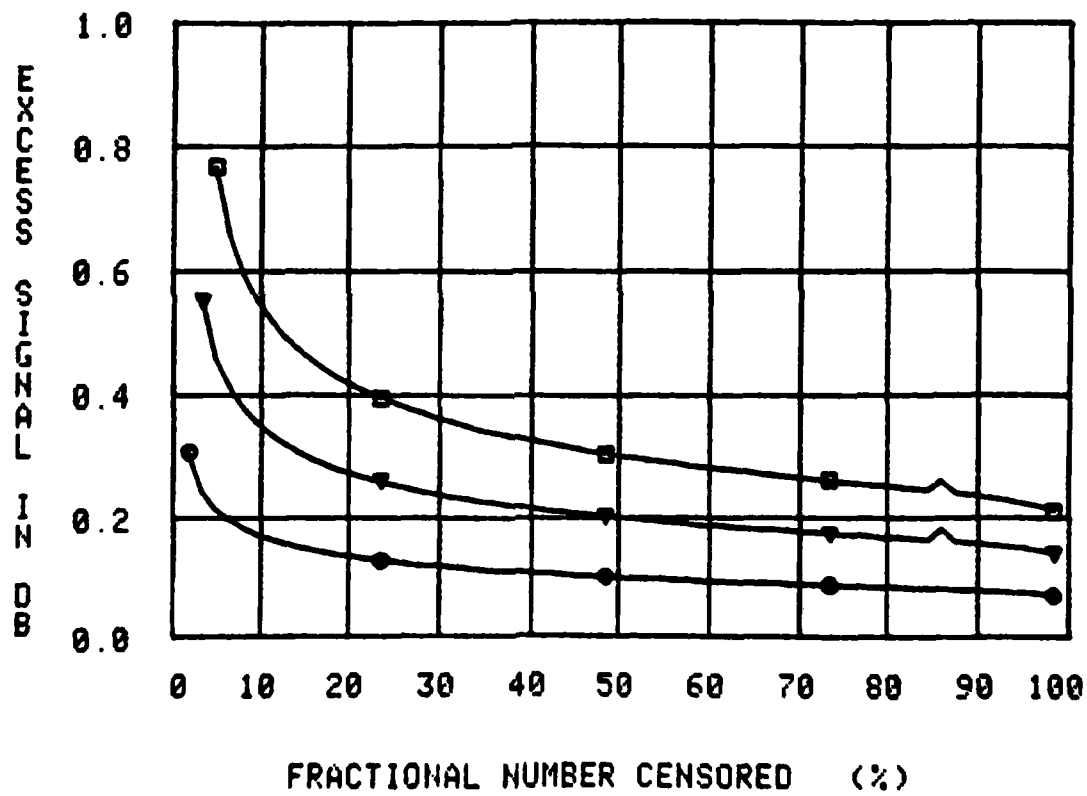


Figure 9b.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$

N = 4

▲ NI = 0

MDS<sub>P</sub> = 5.23

M = 8

○ NI = 1

▼ NI = 2

□ NI = 3

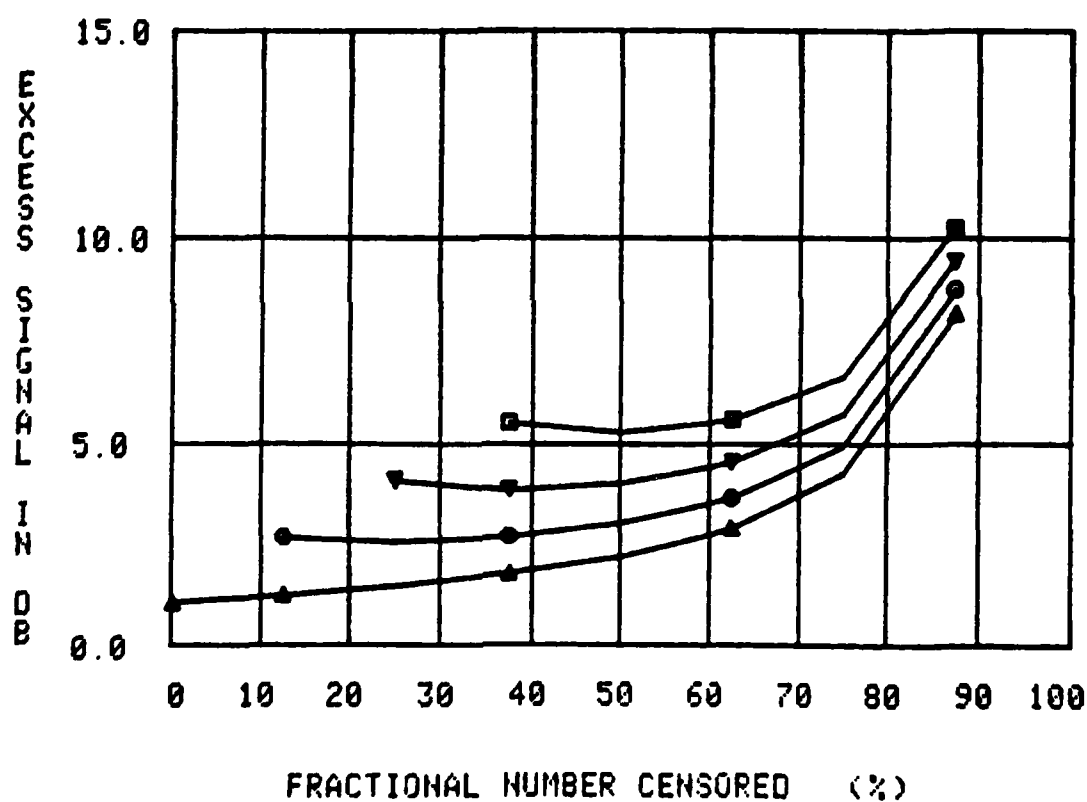


Figure 10a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 4

M = 8

○ NI = 1  
▼ NI = 2  
□ NI = 3

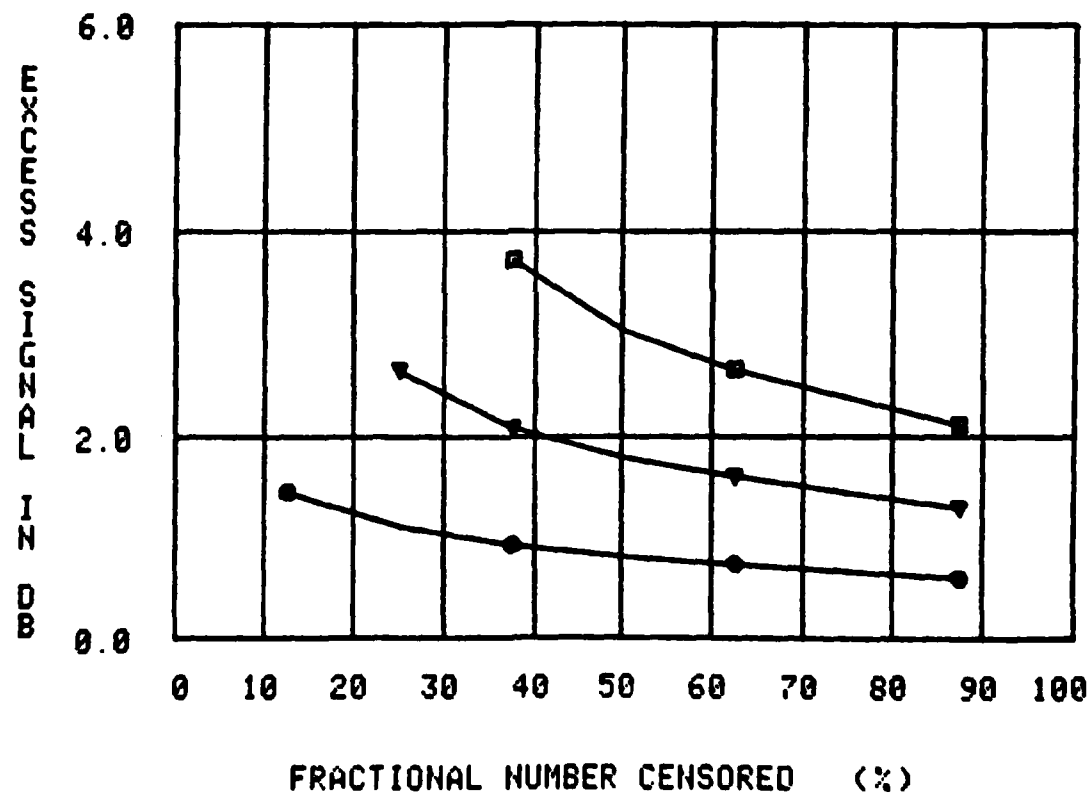


Figure 10b.



# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$

N = 4

▲ NI = 0

MDS<sub>p</sub> = 5.23

M = 16

○ NI = 1

▼ NI = 2

□ NI = 3

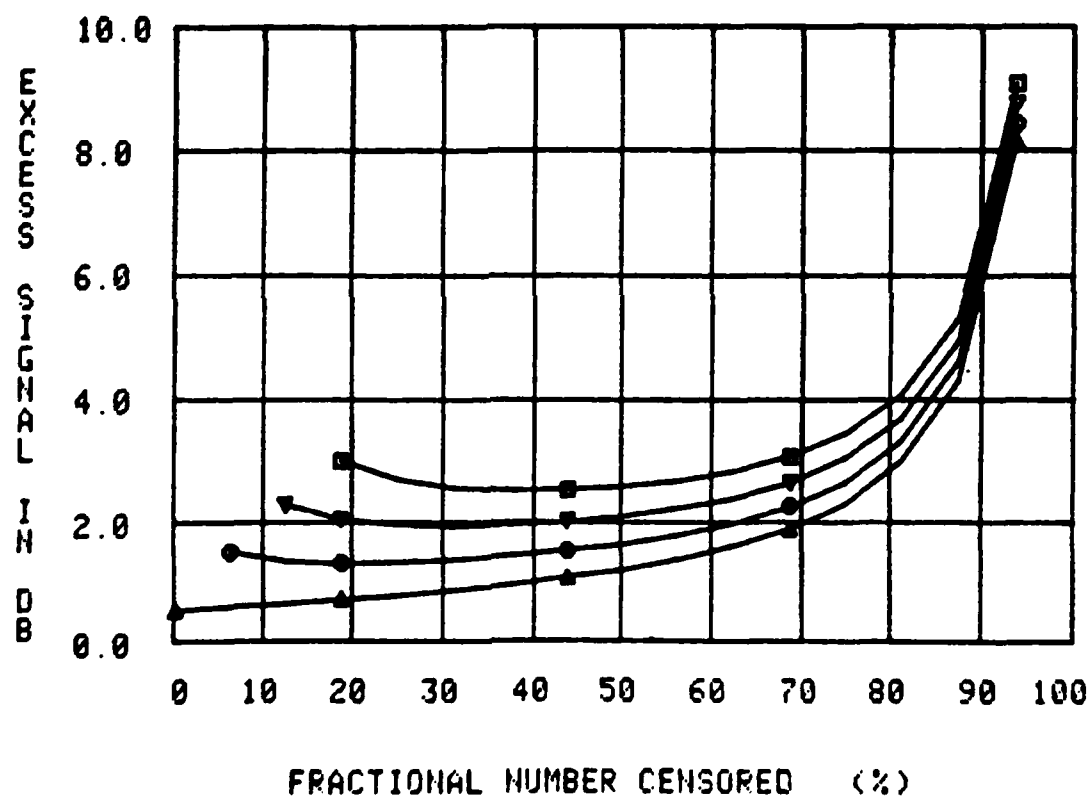


Figure 11a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 4

M = 16

○ NI = 1  
▼ NI = 2  
□ NI = 3

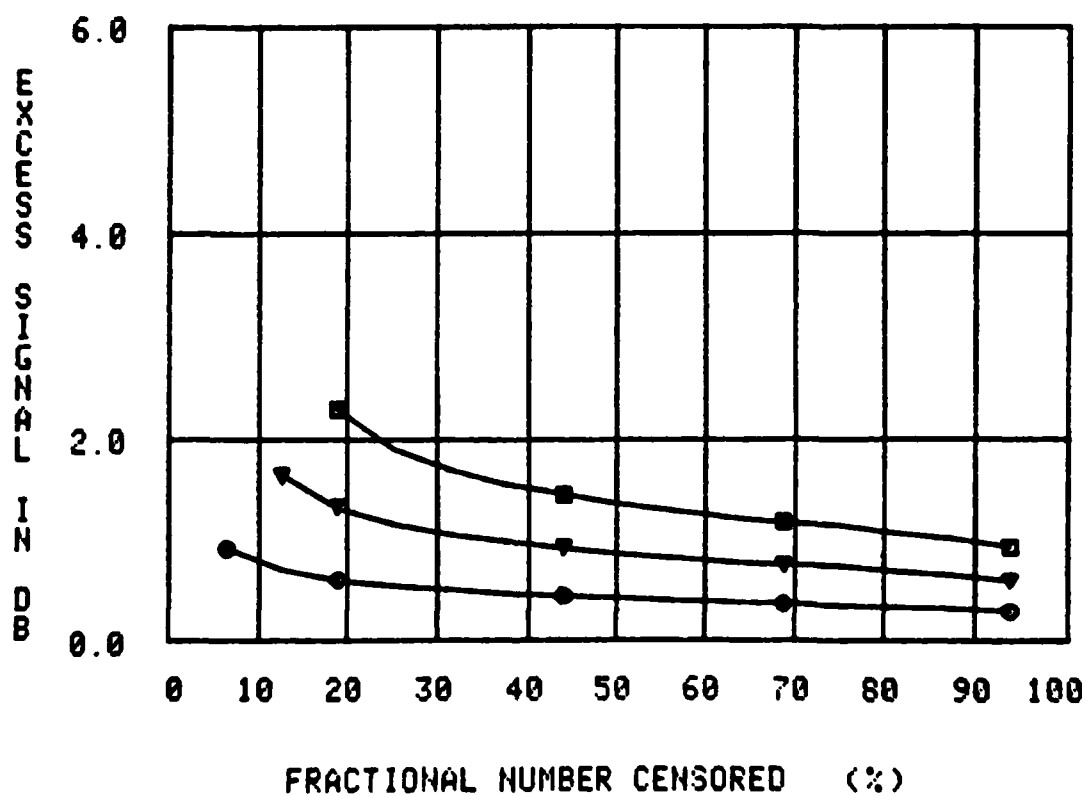


Figure 11b.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$   
MDS<sub>P</sub> = 5.23

N = 4  
M = 32

▲ NI = 0  
○ NI = 1  
▼ NI = 2  
□ NI = 3

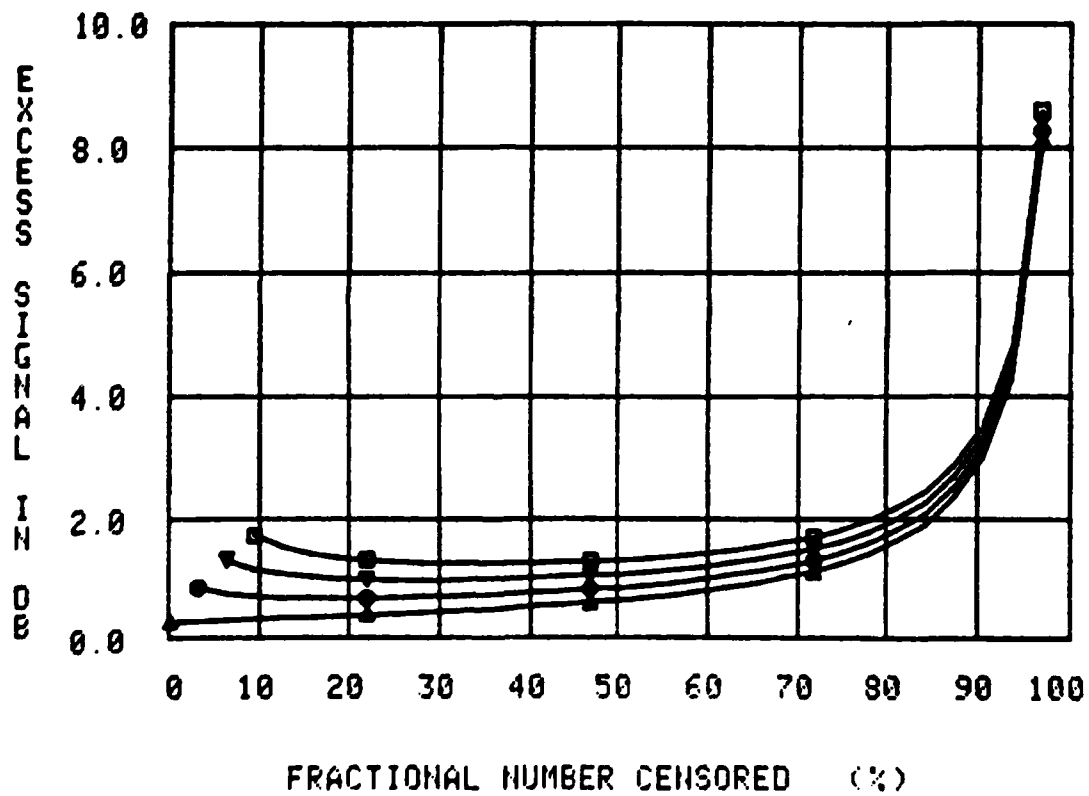
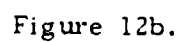


Figure 12a.

PFA =  $10^{-4}$       N = 4      M = 32       $\begin{matrix} \text{O} \\ \text{V} \\ \text{B} \end{matrix} \begin{matrix} \text{NI} \\ \text{NI} \\ \text{NI} \end{matrix} = \begin{matrix} 1 \\ 2 \\ 3 \end{matrix}$



# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$   
MDS<sub>P</sub> = 5.23

N = 4  
M = 64

△ NI = 0  
○ NI = 1  
▽ NI = 2  
□ NI = 3

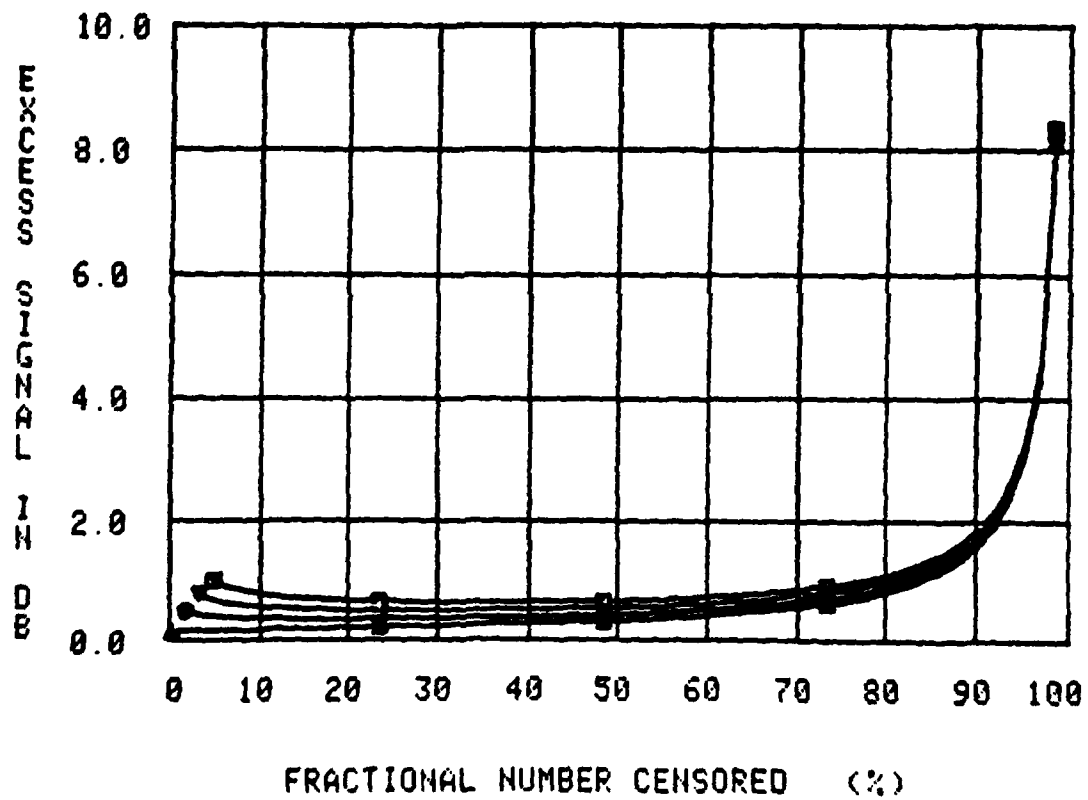


Figure 13a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 4

M = 64

○ NI = 1  
▼ NI = 2  
□ NI = 3

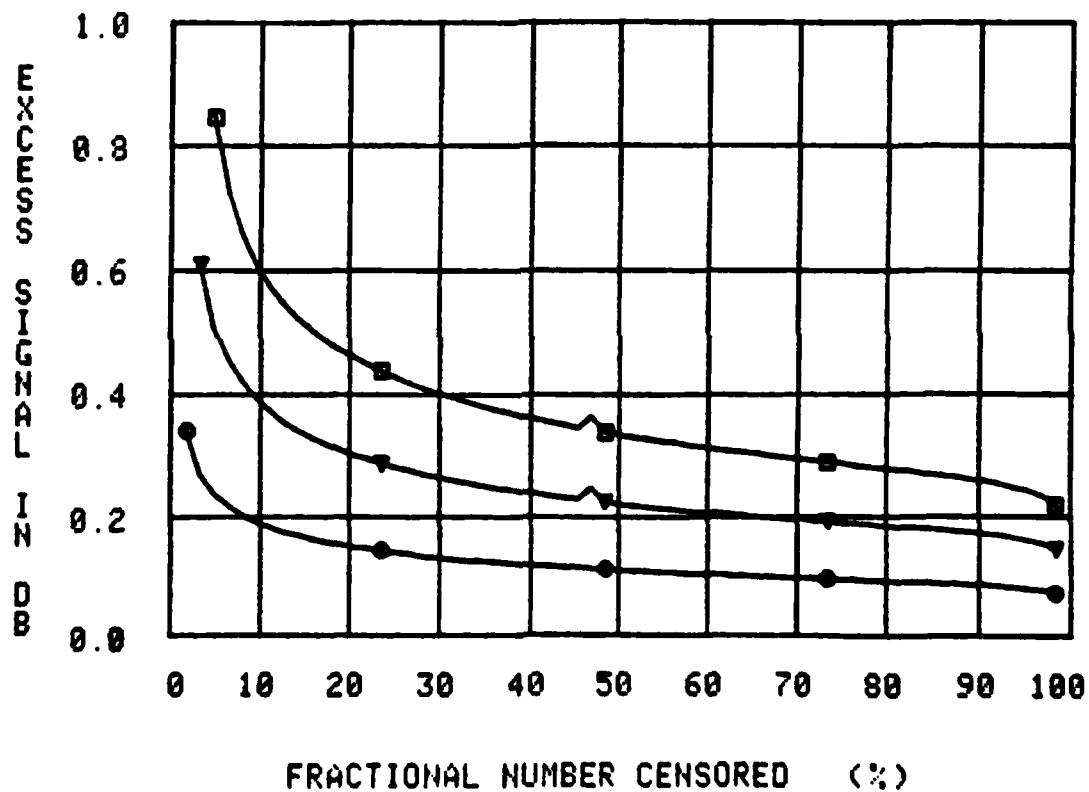


Figure 13b.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$

N = 8

▲ NI = 0

MDS<sub>F</sub> = 3.01

M = 8

○ NI = 1

▼ NI = 2

□ NI = 3

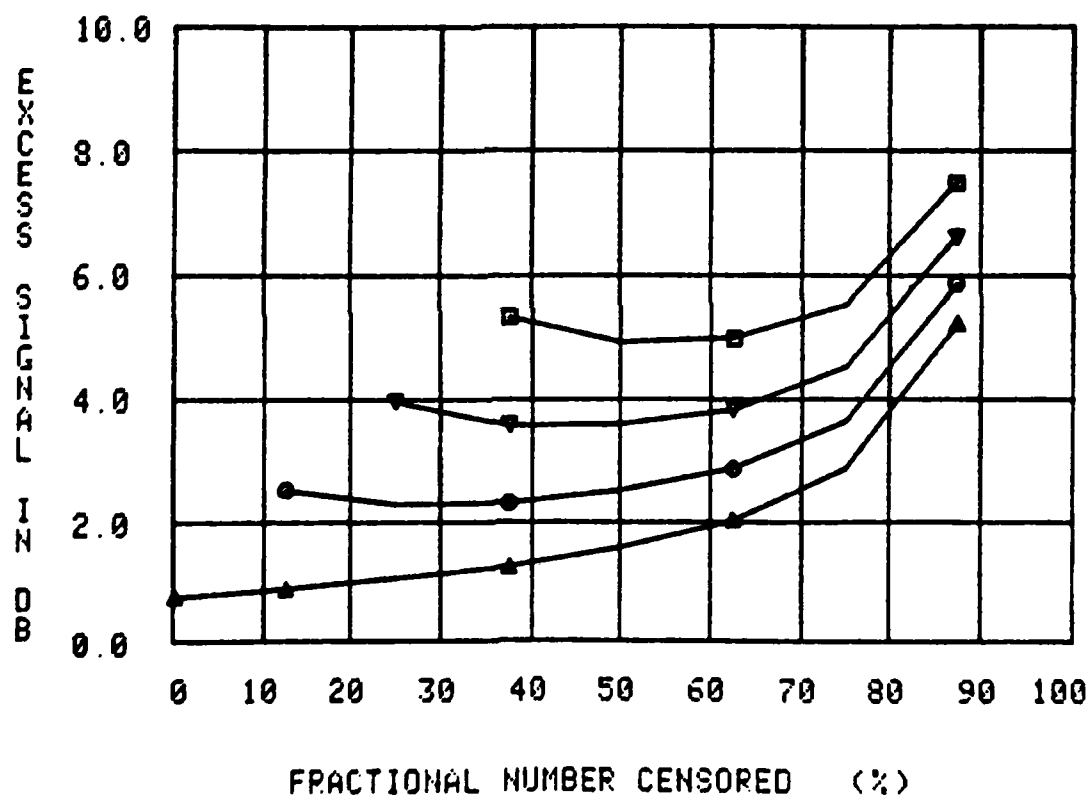


Figure 14a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 8

M = 8

○ NI = 1  
▼ NI = 2  
□ NI = 3

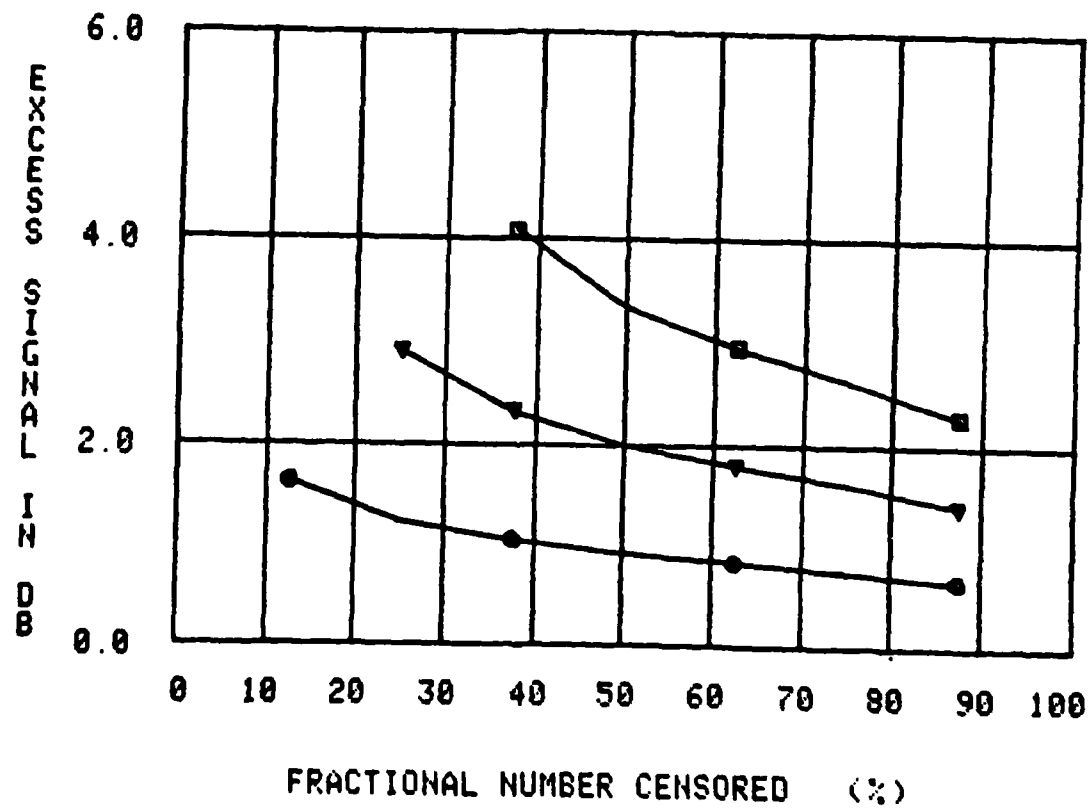


Figure 14b.



# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

FFA =  $10^{-4}$   
MDS<sub>p</sub> = 3.01

N = 8  
M = 16

▲ NI = 0  
○ NI = 1  
▼ NI = 2  
□ NI = 3

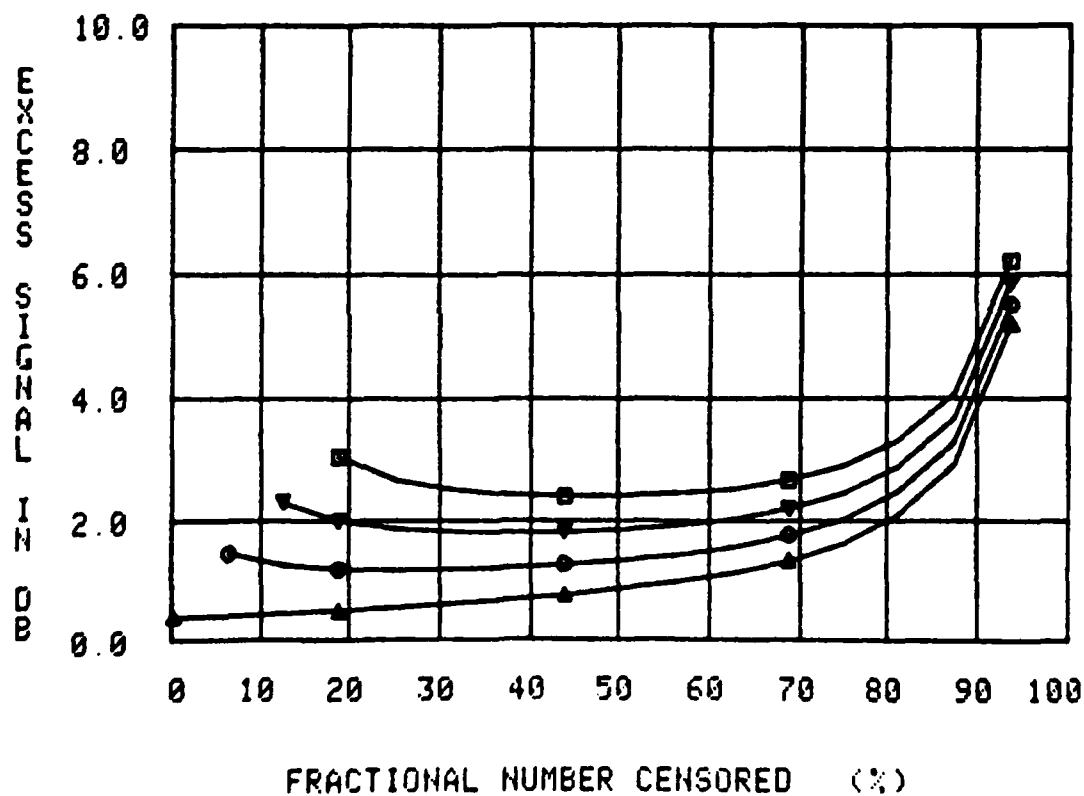


Figure 15a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 8

M = 16

○ NI = 1  
▼ NI = 2  
□ NI = 3

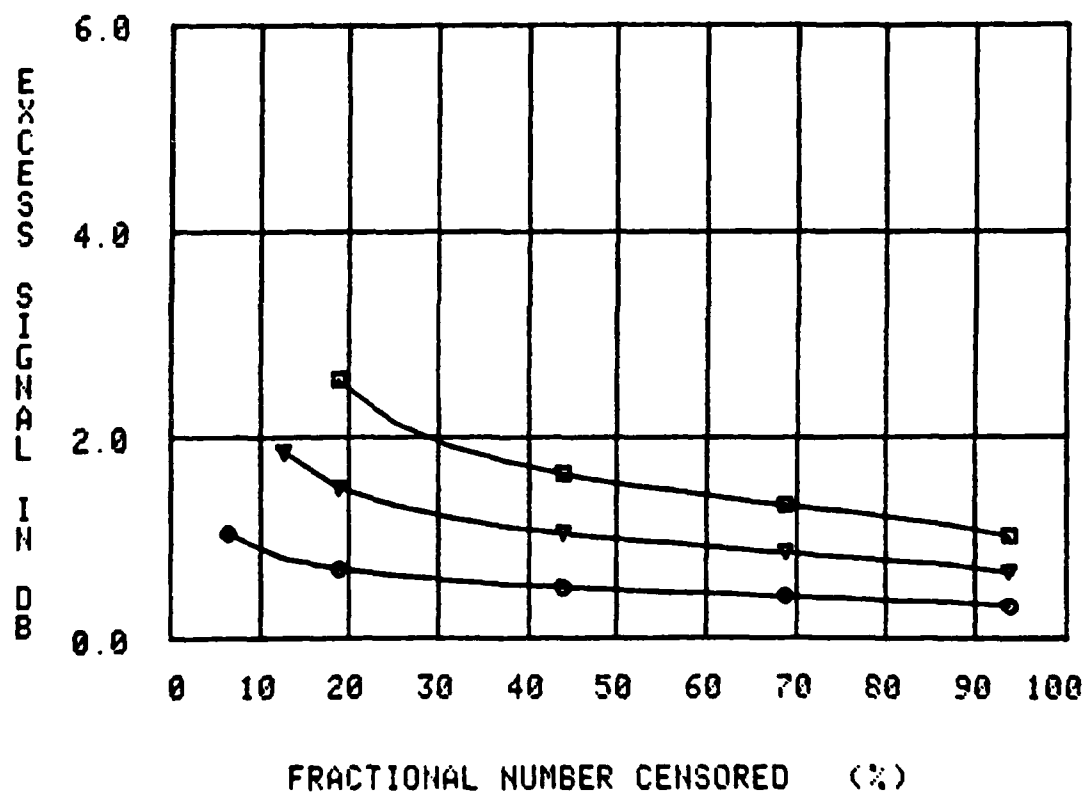


Figure 15b.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$   
MDS<sub>P</sub> = 3.01

N = 8  
M = 32

▲ NI = 0  
○ NI = 1  
▼ NI = 2  
□ NI = 3

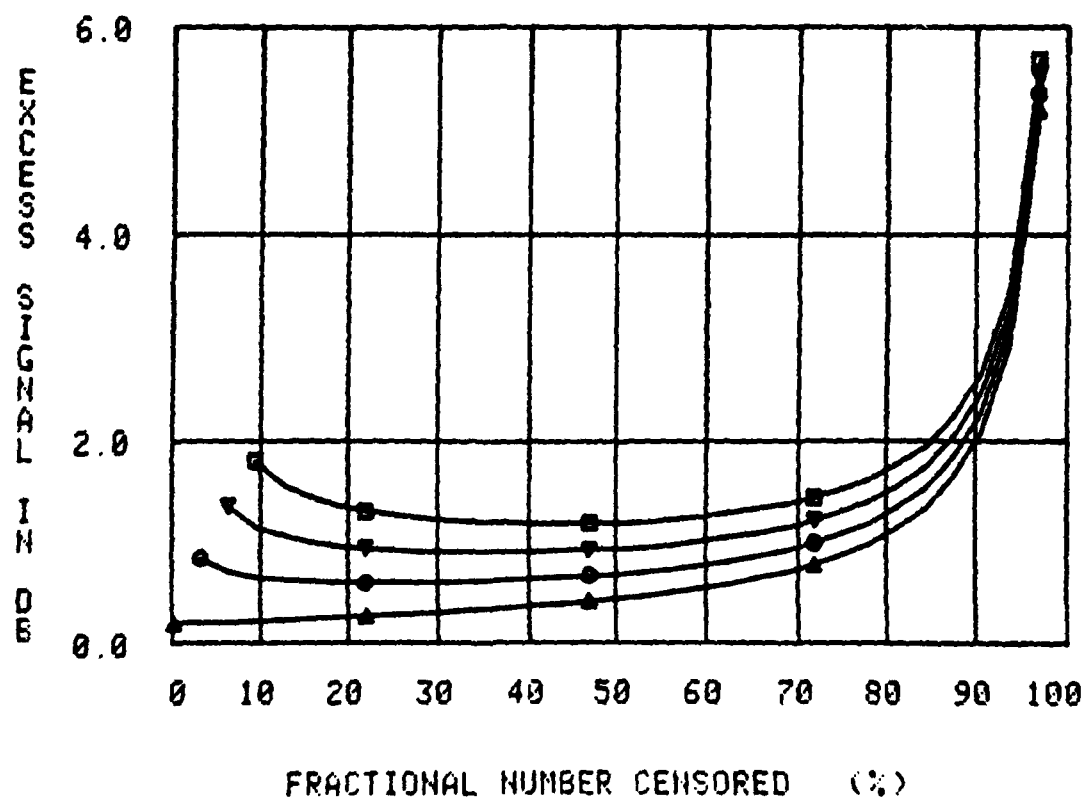


Figure 16a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 8

M = 32

○ NI = 1  
▼ NI = 2  
□ NI = 3

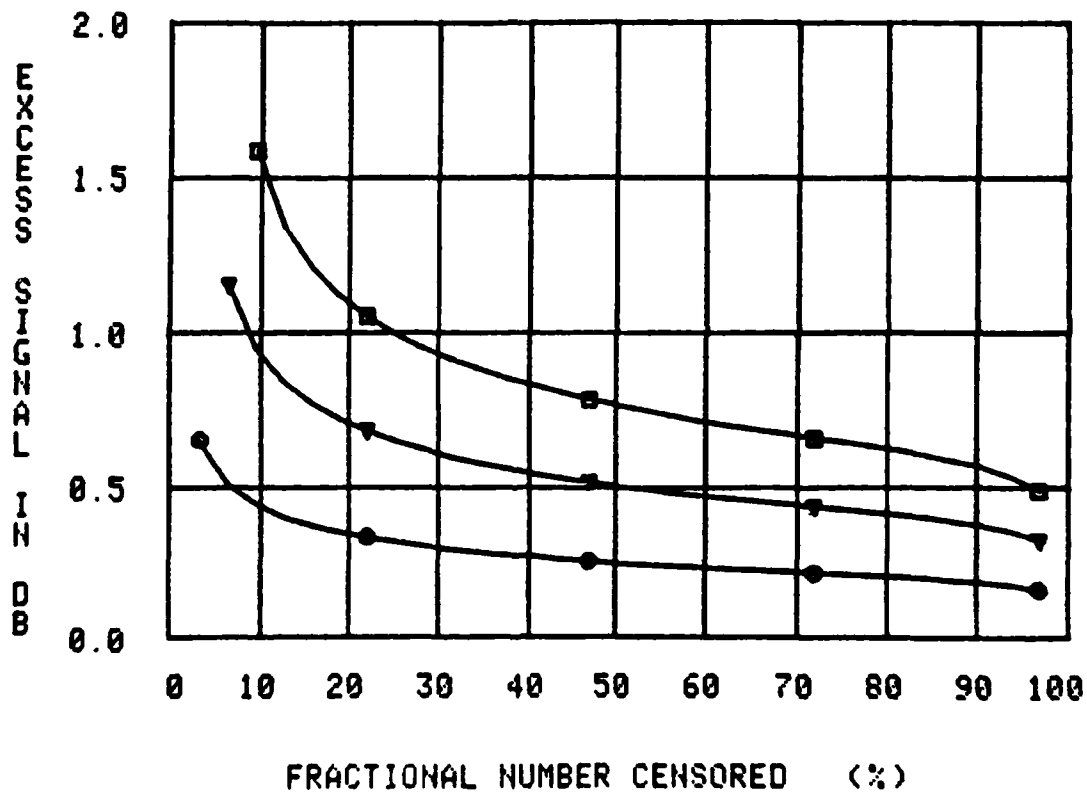


Figure 16b.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$

N = 8

▲ NI = 0

MDS<sub>P</sub> = 3.01

M = 64

○ NI = 1

▼ NI = 2

□ NI = 3

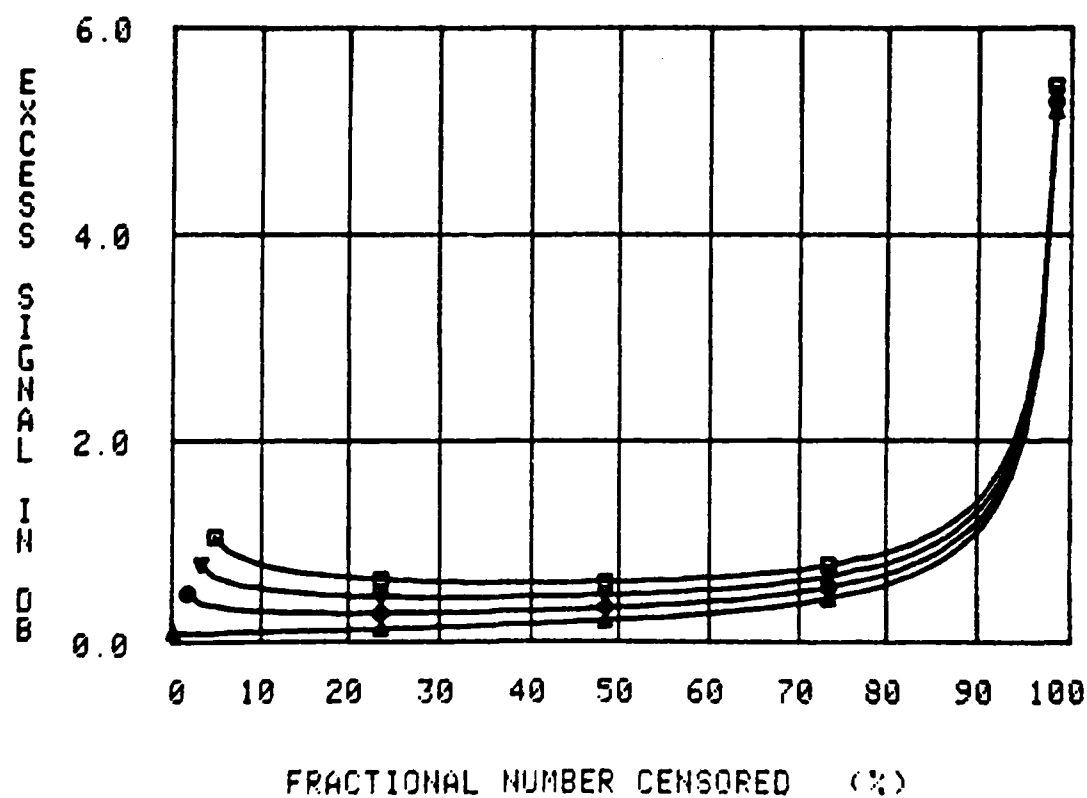


Figure 17a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MOS FOR CMLD

PFA =  $10^{-4}$       N = 8      M = 64

○ NI = 1  
▼ NI = 2  
□ NI = 3

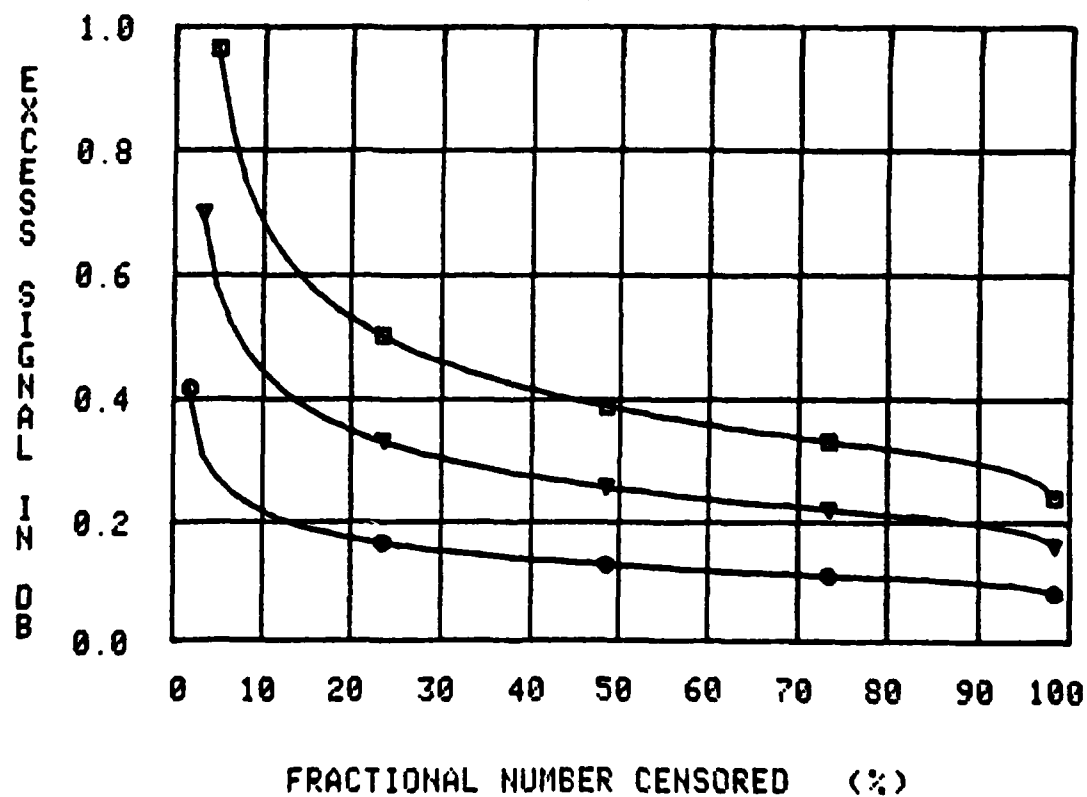


Figure 17b.

practical interest (i.e., moderately large  $M$ ) this trade-off will suggest moderately large fractional numbers censored (of order 50%) if the interference density is expected to be high. For  $N$  equal one and small  $M$ , the very large additional CFAR loss caused by censoring will more than offset the robustness gains except in the most dense interference environments.

In order to investigate the onset of the performance loss due to interference as a function of the interference-to-noise power ratio (INR), a set of Monte Carlo simulations covering the range  $N=1$  or  $8$ ;  $M=8$ ,  $a=0,1,2,4$  or  $6$ ; and  $NI = 1, 2$ , or  $3$  were run and the results in the form of plots of EXS (referenced to the optimal energy detector) versus INR are given in Figures 18 through 23. When more than one interferer is present, ( $NI = 2$  or  $3$ ) the interferers are independent and have the same INR. These results plainly show that when the number of interferers ( $NI$ ) is less than or equal to the number of samples censored from above ( $a$ ), the performance loss reaches its predicted [from Figures 2(a) and 14(a)] asymptotic value in the range of INR from about 4 dB to 16 dB. In contrast, when the number of interferers is greater than the number of samples censored, the performance loss is a monotonically increasing function of the INR.

### 2.3 The Two-Pass CBA-CMLD

The fact that the CMLD has a predictable (from the number of interferers) performance loss in the presence of  $NI(< a)$  large interferers, indicates a two-pass implementation of the CMLD should be able to recover the loss due to interference when the interferers are detectable.

In the first pass, the detection statistic is calculated as in the CBA-CMLD and the initial detections are made. Then, for each test cell, a count is made of the number of first pass detections made in its noise reference window. Under the assumption that each detection can be modeled as a large interferer, a second pass,

# CBA-CMLD PERFORMANCE IN THE PRESENCE OF INTERFERENCE

$N = 1$      $PFA = 10^{-4}$      $MDS_p = 10.90 \text{ dB}$   
 $M = 8$      $NI = 1$      $a = \text{NO. CENSORED}$   
 10,000 SIMULATION RUNS FROM ABOVE

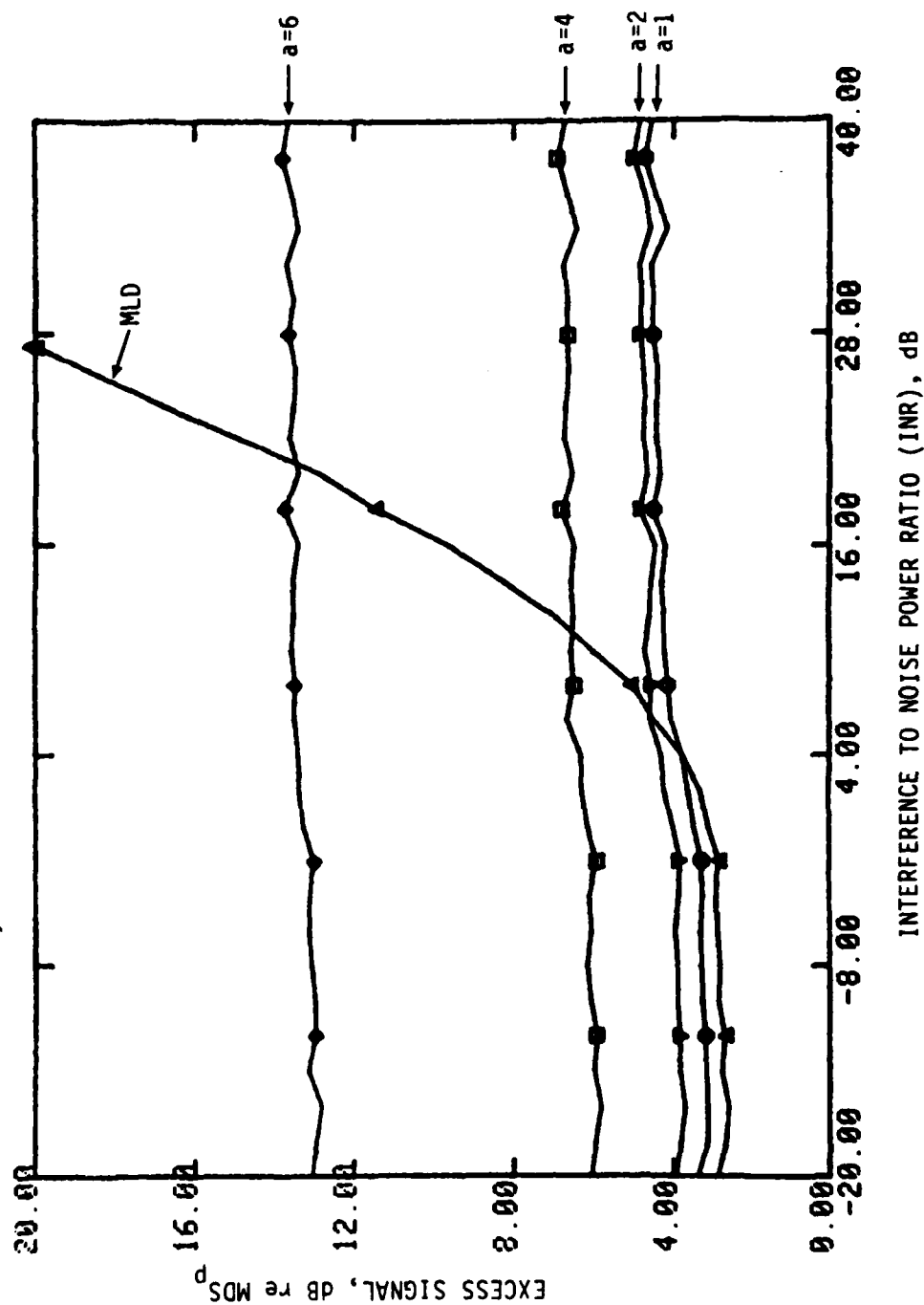
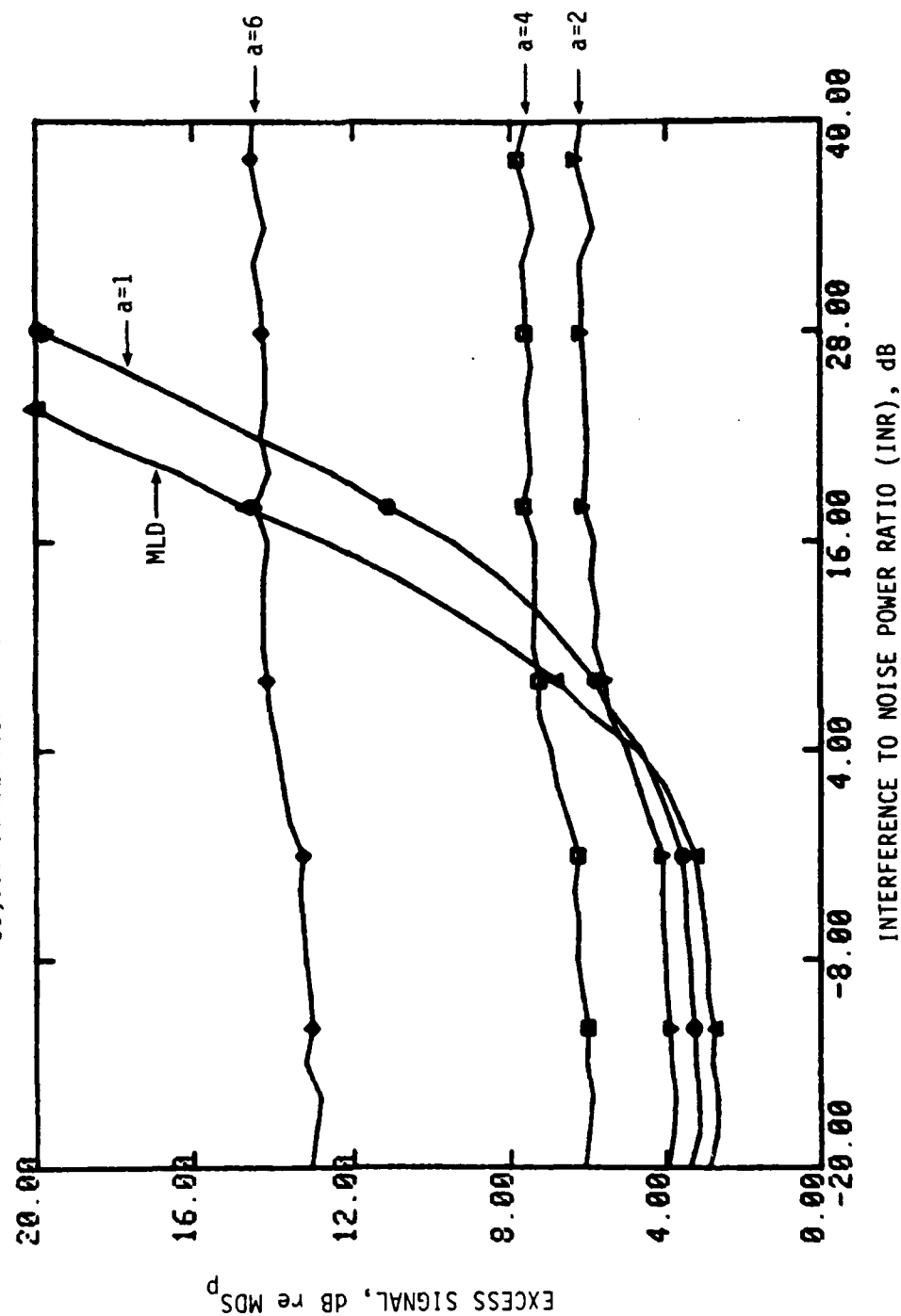


Figure 18.



$N = 1$     $PFA = 10^{-4}$     $MDS_p = 10.90$  dB  
 $M = 8$     $NI = 2$     $a = \text{NO. CENSORED FROM ABOVE}$   
 10 000 SIMULATION RUNS



**Figure 19.**

# CBA-CMLD PERFORMANCE IN THE PRESENCE OF INTERFERENCE

$N = 1$      $PFA = 10^{-4}$      $MDS_p = 10.90 \text{ dB}$   
 $M = 8$      $NI = 3$      $a = \text{NO. CENSORED}$   
 10,000 SIMULATION RUNS FROM ABOVE

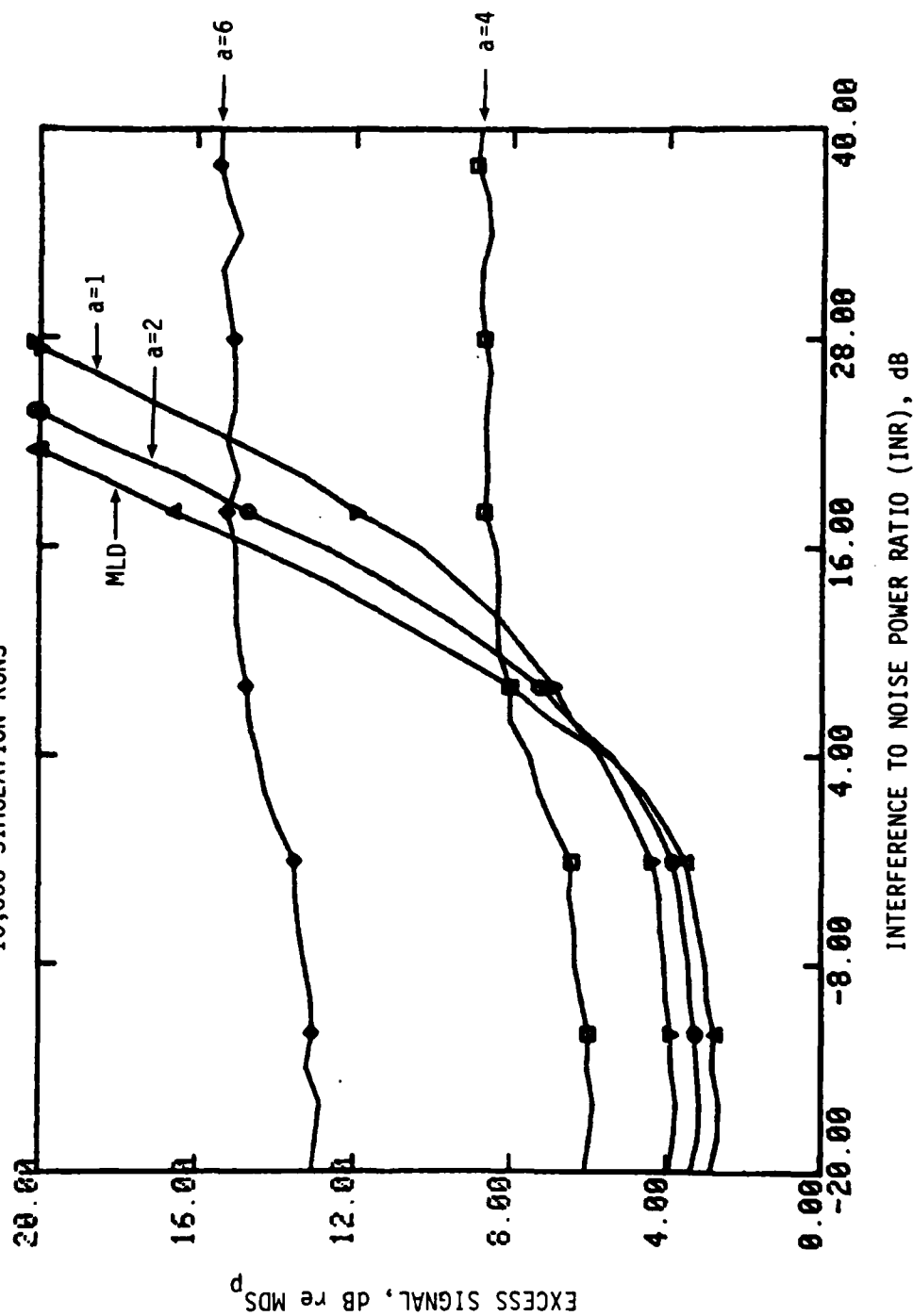


Figure 20.

# CBA-CMLD PERFORMANCE IN THE PRESENCE OF INTERFERENCE

$N = 8$      $PFA = 10^{-4}$      $MDS_p = 3.01 \text{ dB}$   
 $M = 8$      $NI = 1$      $a = \text{NO. CENSORED}$   
 4,000 SIMULATION RUNS FROM ABOVE

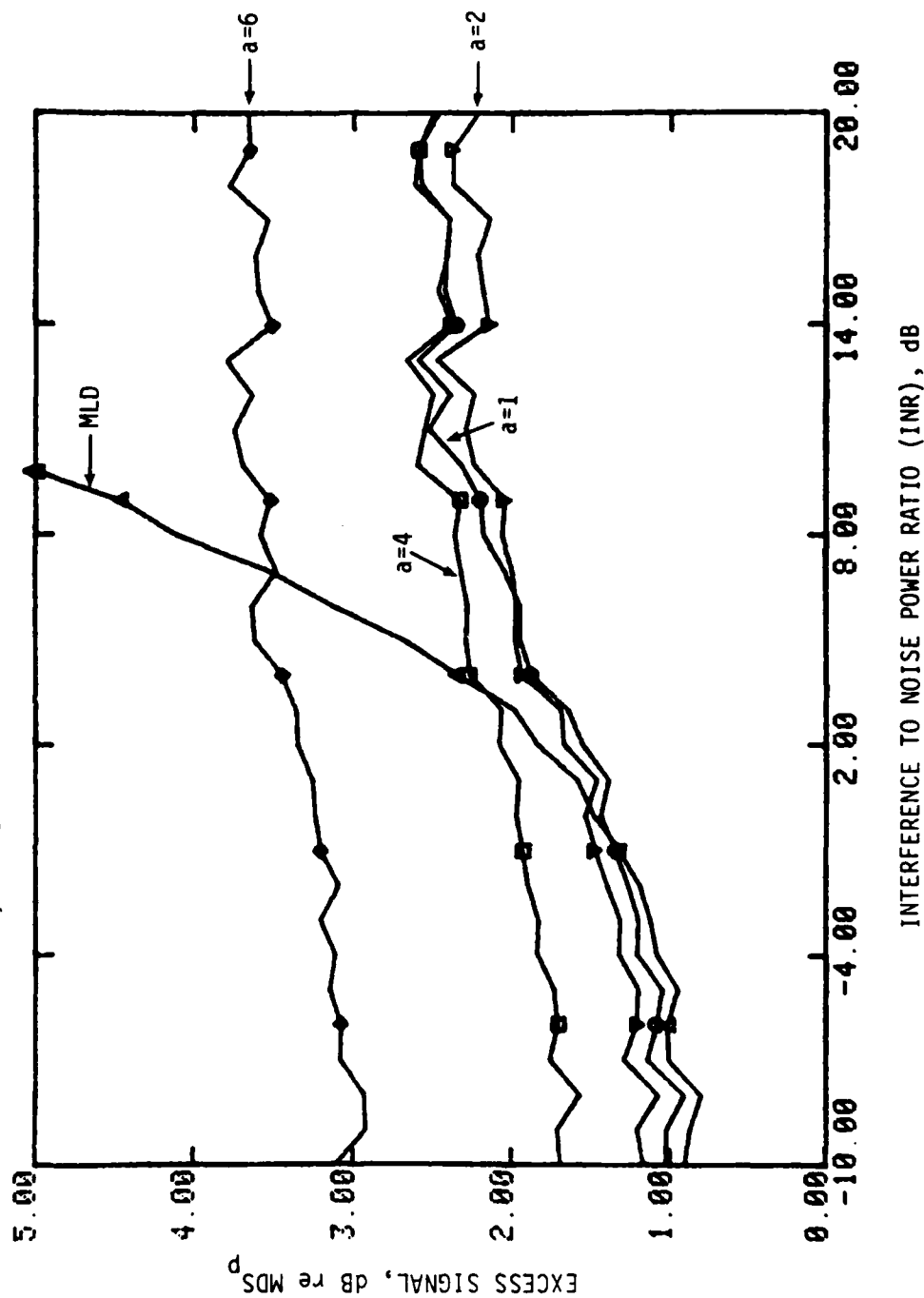
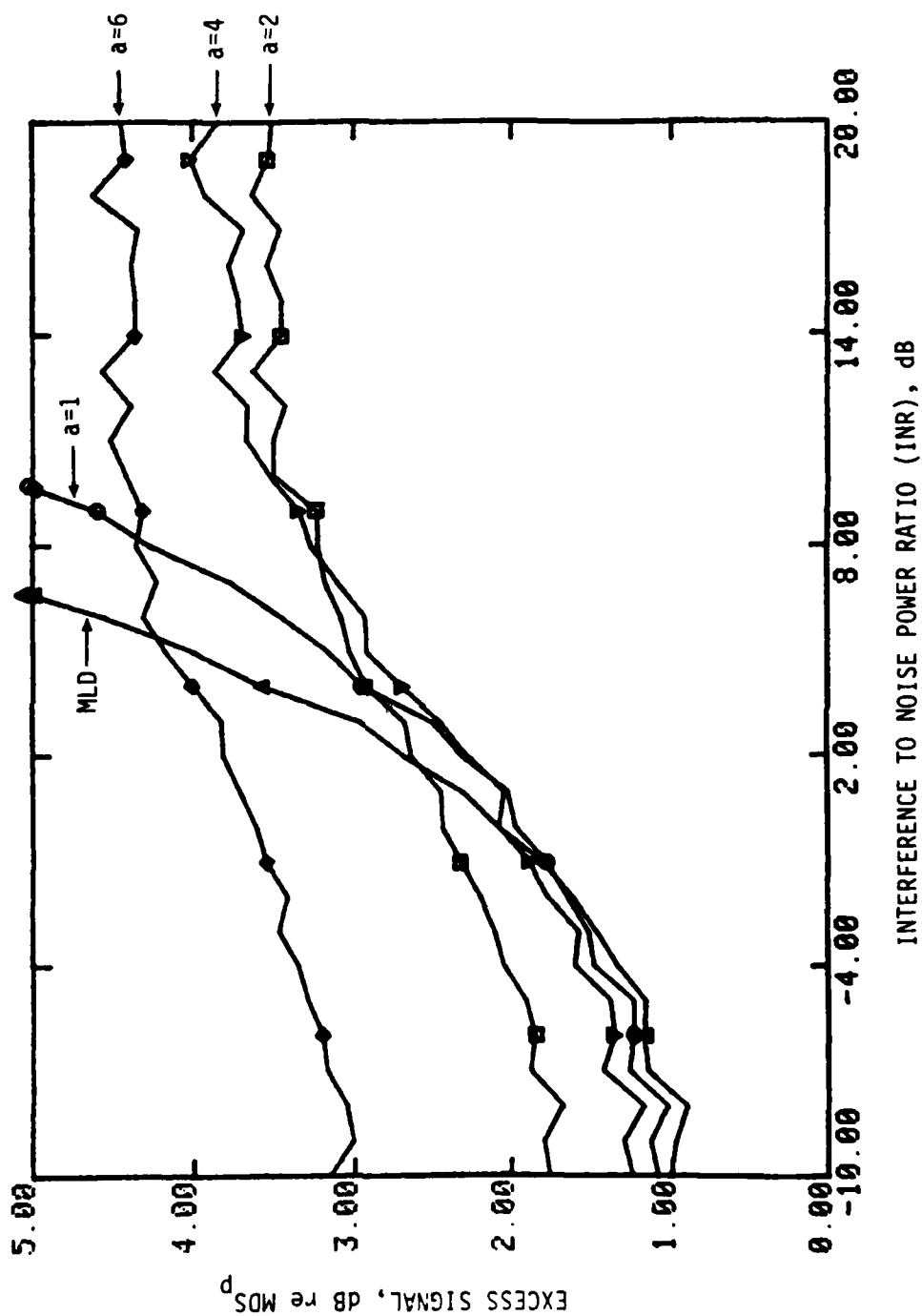


Figure 21.

### CBA-CMLD PERFORMANCE IN THE PRESENCE OF INTERFERENCE

N = 8    PFA =  $10^{-4}$     MDS<sub>p</sub> = 3.01 dB  
M = 8    NI = 2    a = NO. CENSORED  
4,000 SIMULATION RUNS    FROM ABOVE



**Figure 22.**

# CBA-CMLD PERFORMANCE IN THE PRESENCE OF INTERFERENCE

$N = 8$      $PFA = 10^{-4}$      $MDS_p = 3.01 \text{ dB}$   
 $M = 8$      $NI = 3$      $a = \text{NO. CENSORED FROM ABOVE}$   
 4,000 SIMULATION RUNS

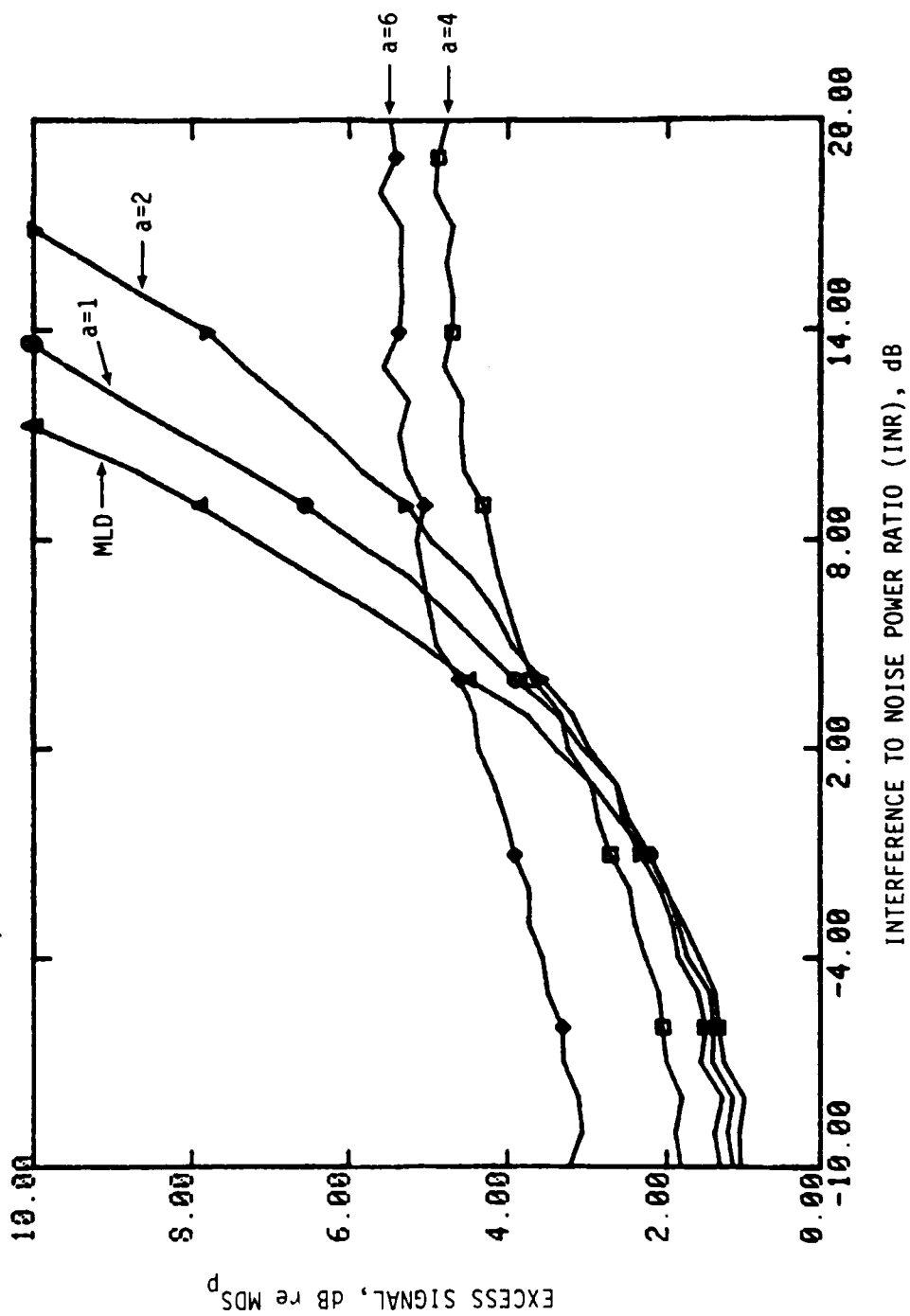


Figure 23.

consisting of re-thresholding the test bin (with no additional computations) with a threshold predicted from the analytical asymptotic expressions is made.

While the analysis of such a detector even under  $H_0$  would be exceedingly difficult, the performance results under  $H_0$  are believed to be very well approximated by the first pass analysis [i.e., the CBA-CMLD results in Figures 2(a) through 17(a) for  $NI=0$ ]. This is true because the error in the probability of false-alarm caused by using thresholds for the CBA-CMLD in the two pass detector is of the order of  $M$  times the probability of false-alarm squared, and therefore of little practical significance. For this reason and because of the large cost of false-alarm simulations, no verifying false-alarm simulations were done.

The two-pass CBA-CMLD is implemented by using the CBA-CMLD (Section 2.1) as a first pass, then a count is made of the number of first-pass detections in the noise reference window of each test bin as follows:

First, let

$$I(j) = \begin{cases} 1 & \text{if } D(j) > T_0 \\ 0 & \text{if } D(j) \leq T_0 \end{cases}, \quad (7)$$

where  $D(j)$  is the CBA-CMLD detection statistic calculated in the first pass processing and  $T_0$  is the CBA-CMLD threshold for the desired probability of false alarm, as in (6). Then the number of detections in the noise reference window is:

$$NI(j) = \sum_{\substack{n=j+\frac{M}{2} \\ n=j-\frac{M}{2} \\ n \neq j}} I(n) . \quad (8)$$

Then, we re-threshold the first-pass detection statistic,  $D(j)$ , to complete the detection process

$$D(j) \geq T_{NI(j)} \quad (9)$$

where  $T_{NI}$  is the analytically obtained threshold appropriate for NI "large" interferers.

#### 2.4 Performance Results for the Two-Pass CBA-CMLD

Figures 24 through 29 were the result of Monte Carlo simulations of the performance of the two-pass CBA-CMLD. They correspond to the same range of parameters as Figures 18 through 23 do for the CBA-CMLD. The performance of the two-pass CBA-CMLD for small or large INR is nearly identical to that of the CBA-CMLD under  $H_0$  ( $NI = 0$ ). For intermediate INRs there is some additional performance loss due to the presence of undetected interferers. This additional loss is summarized in Table 1 in terms of the maximum performance loss and the INR at which the maximum occurs. The two-pass CBA-CMLD has a maximum loss which is generally less than the asymptotic loss for the CBA-CMLD and the region in INR over which a significant loss due to interference existence is relatively small. In addition, for larger  $N$ , the maximum is greatly reduced in importance and extent (in INR) over the case for  $N$  equal to one.

To further clarify the performance differences between the CBA-CMLD and the two-pass CBA-CMLD, Figures 18 and 24 have been combined into Figure 30 and Figures 21 and 27 have been combined into Figure 31. In these figures, the difference in performance between the CBA-CMLD and the two-pass CBA-CMLD becomes significant at an INR for the corresponding maximum EXS in Table 1. Also, the performance of the two-pass CBA-CMLD rapidly returns to the performance under  $H_0$  for INRs greater than this value.

It should be noted that only a very small amount of additional processing (i.e., the counting of first-pass detections and re-thresholding) is needed for the two-pass CBA-CMLD, but the resulting performance gains will be significant in heavy interference environments.

# TWO-PASS CBA-CMLD PERFORMANCE IN THE PRESENCE OF INTERFERENCE

$N = 1$     $PFA = 10^{-4}$     $MDS_p = 10.90 \text{ dB}$   
 $M = 8$     $NI = 1$     $a = \text{NO. CENSORED FROM ABOVE}$   
 10,000 SIMULATION RUNS

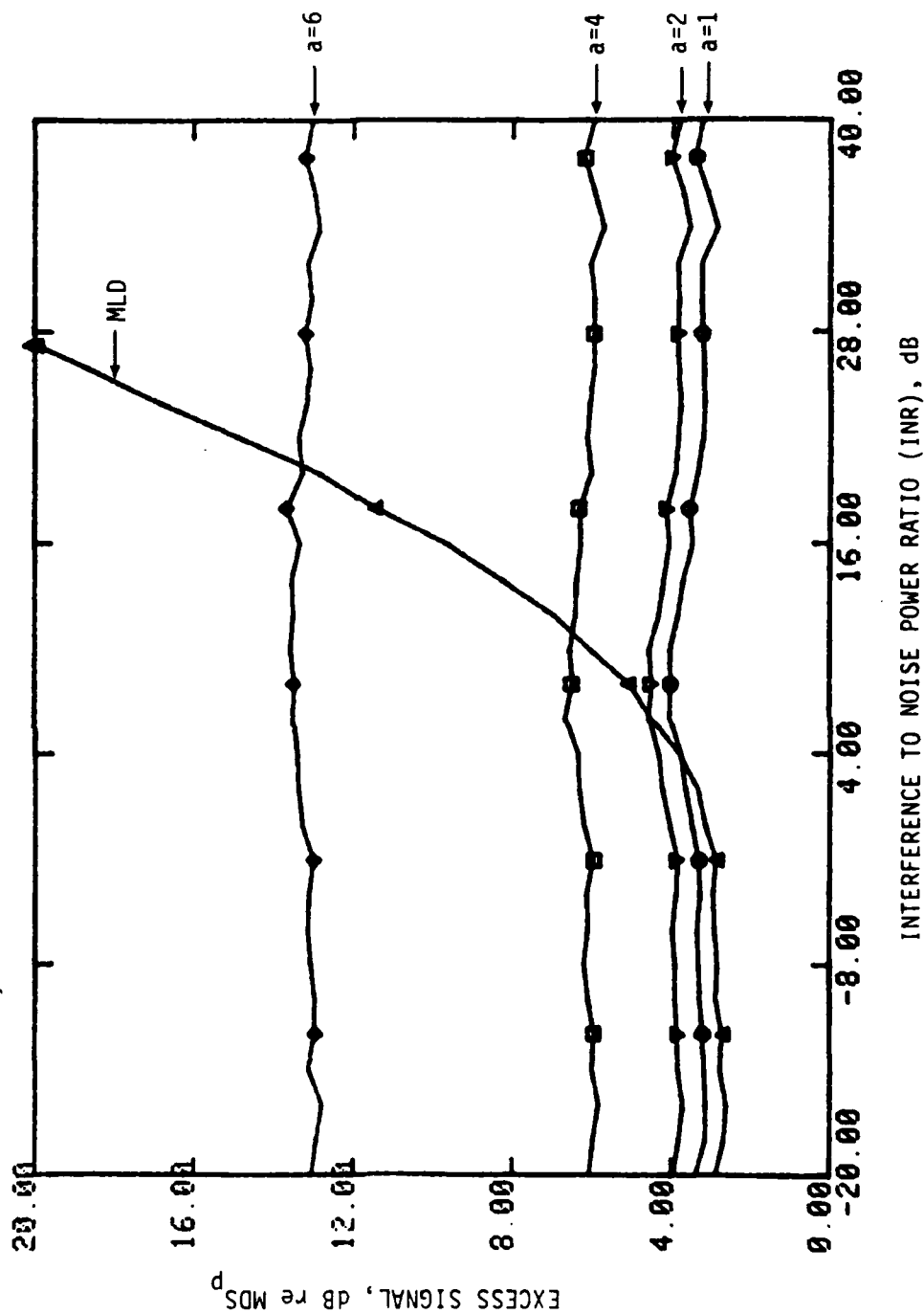


Figure 24.



# TWO-PASS CBA-CMLD PERFORMANCE IN THE PRESENCE OF INTERFERENCE

$N = 1$      $PFA = 10^{-4}$      $MDS_p = 10.90 \text{ dB}$   
 $M = 8$      $NI = 2$      $a = \text{NO. CENSORED FROM ABOVE}$

10,000 SIMULATION RUNS

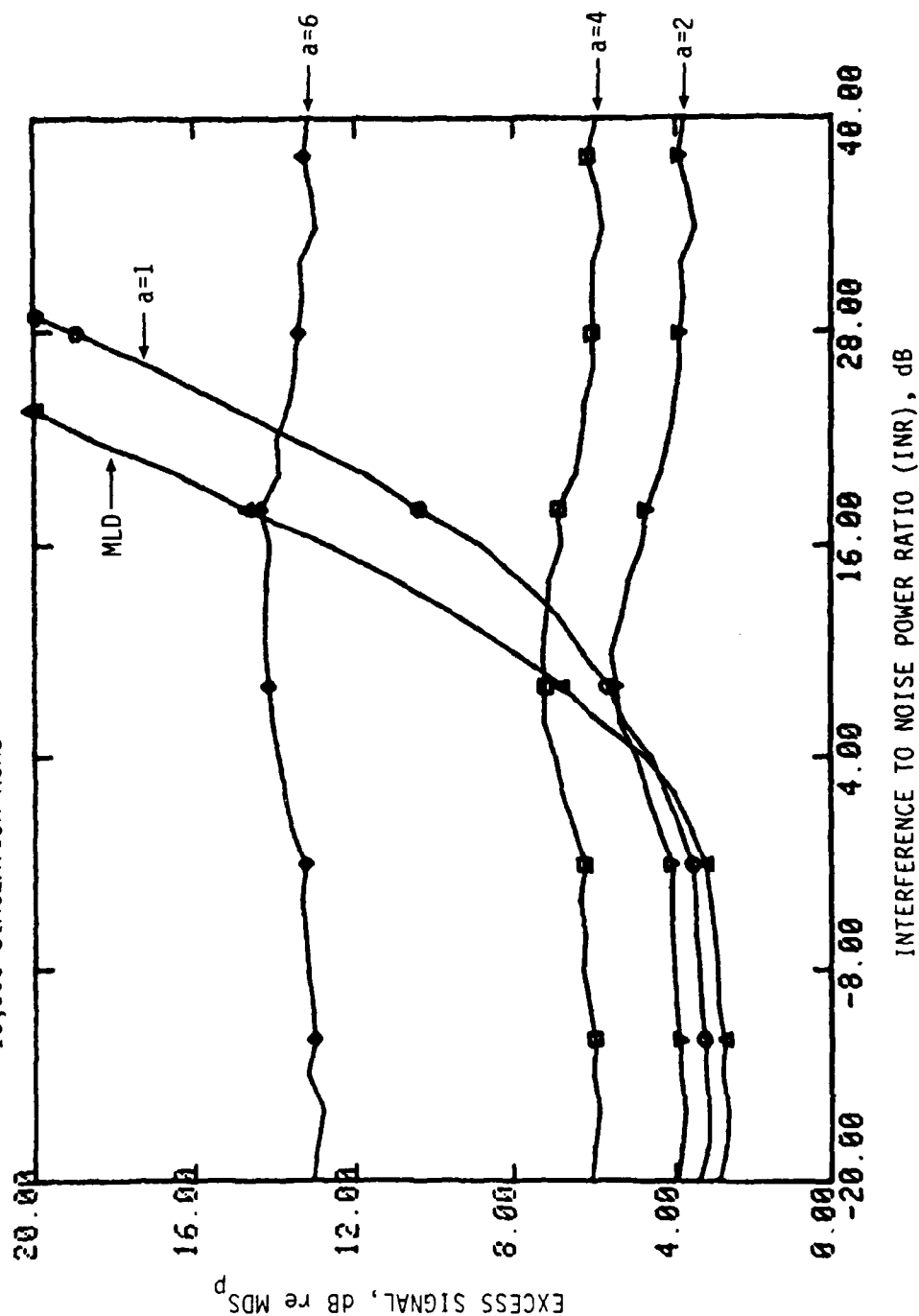


Figure 25.

# TWO-PASS CBA-CMLD PERFORMANCE IN THE PRESENCE OF INTERFERENCE

$N = 1$     $PFA = 10^{-4}$     $MDS_p = 10.90 \text{ dB}$   
 $M = 8$     $NI = 3$     $a = \text{NO. CENSORED FROM ABOVE}$   
 10,000 SIMULATION RUNS

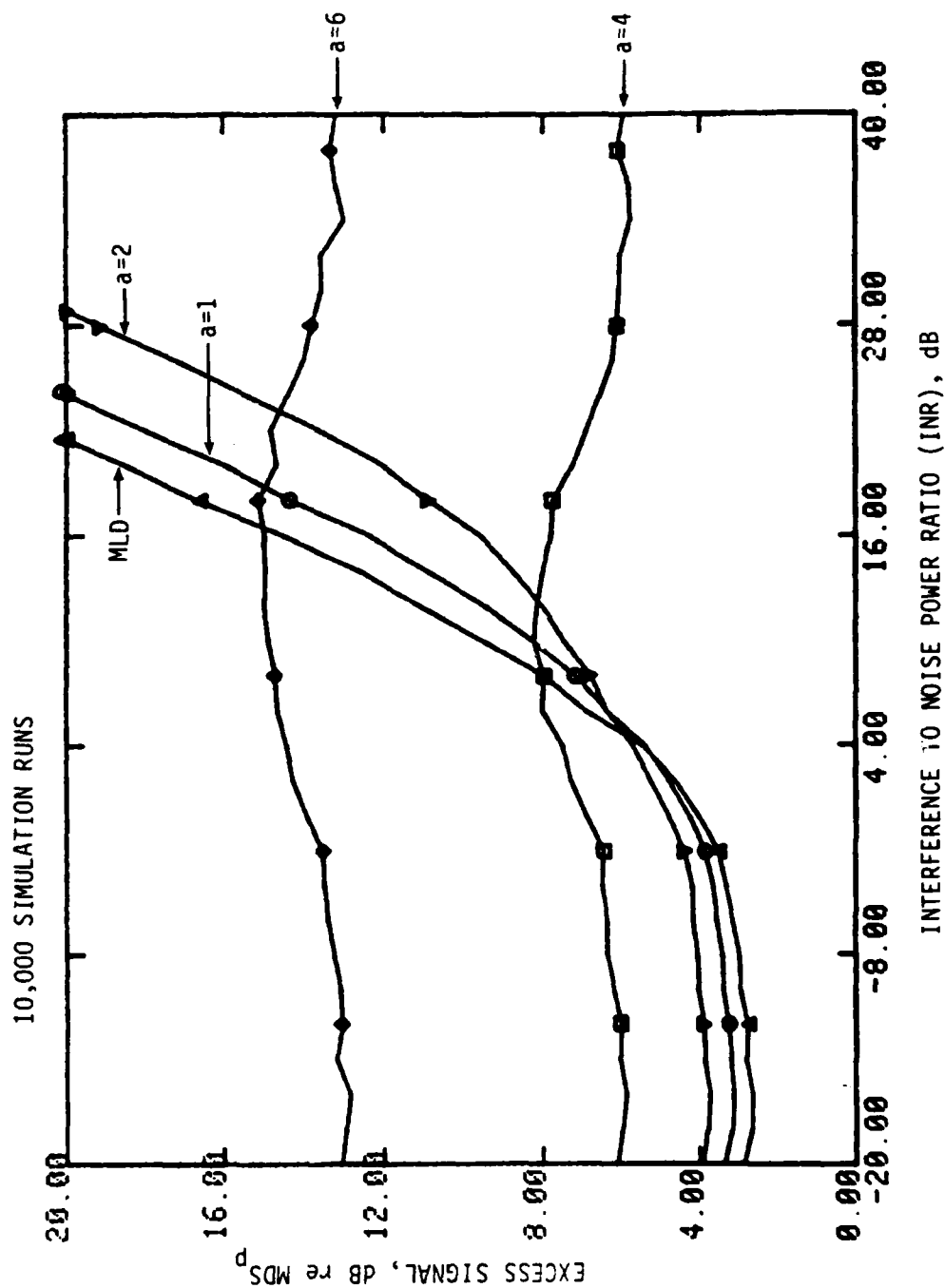


Figure 26.

# TWO-PASS CBA-CMLD PERFORMANCE IN THE PRESENCE OF INTERFERENCE

$N = 8$      $PFA = 10^{-4}$      $MDS_p = 3.01 \text{ dB}$   
 $M = 8$      $NI = 1$      $a = \text{NO. CENSORED FROM ABOVE}$   
 4,000 SIMULATION RUNS

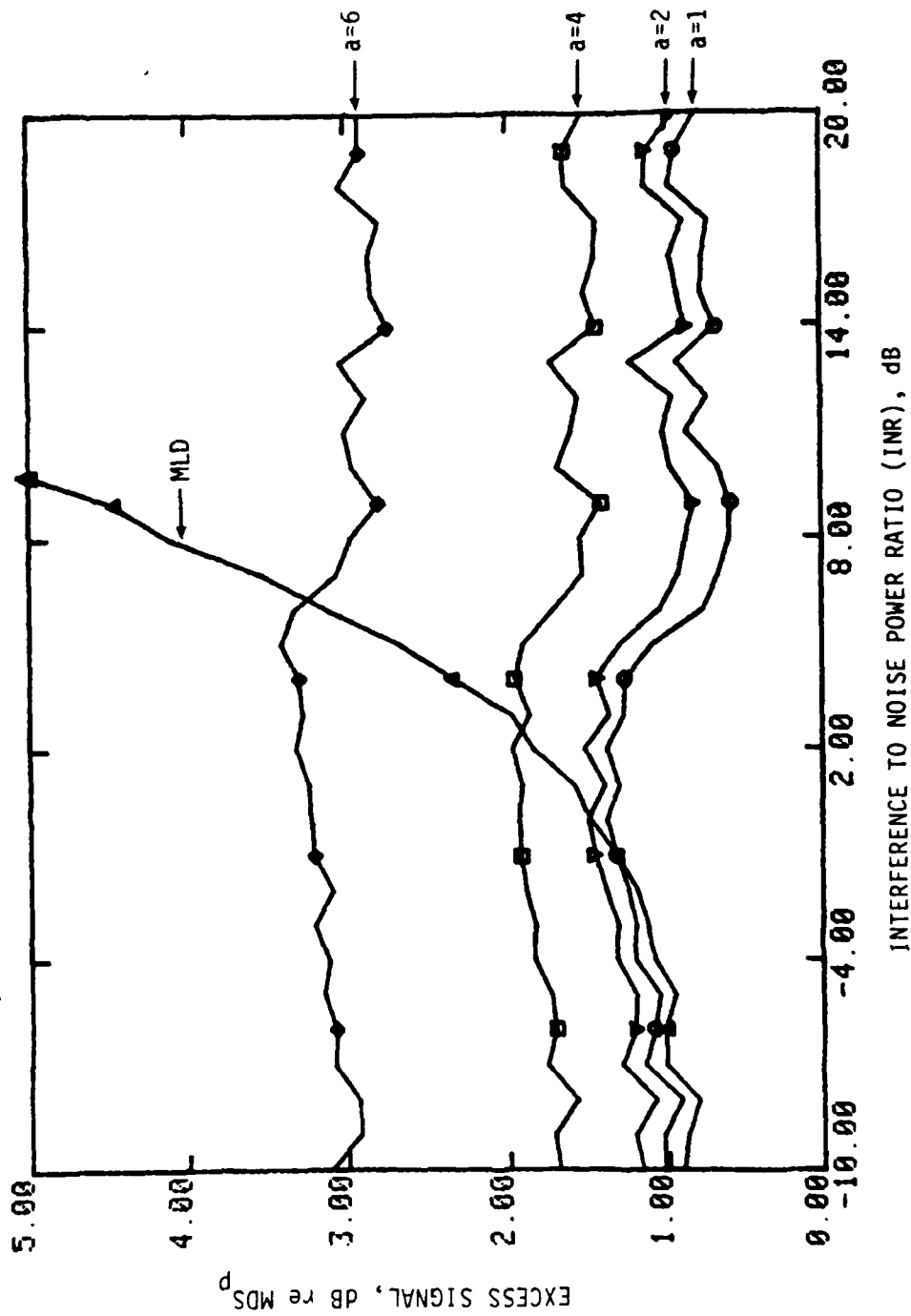


Figure 27.

# TWO-PASS CBA-CMLD PERFORMANCE IN THE PRESENCE OF INTERFERENCE

$N = 8$      $PFA = 10^{-4}$      $MDS_p = 3.01 \text{ dB}$   
 $M = 8$      $NI = 2$      $a = NO.$  CENSORED FROM ABOVE  
 4,000 SIMULATION RUNS

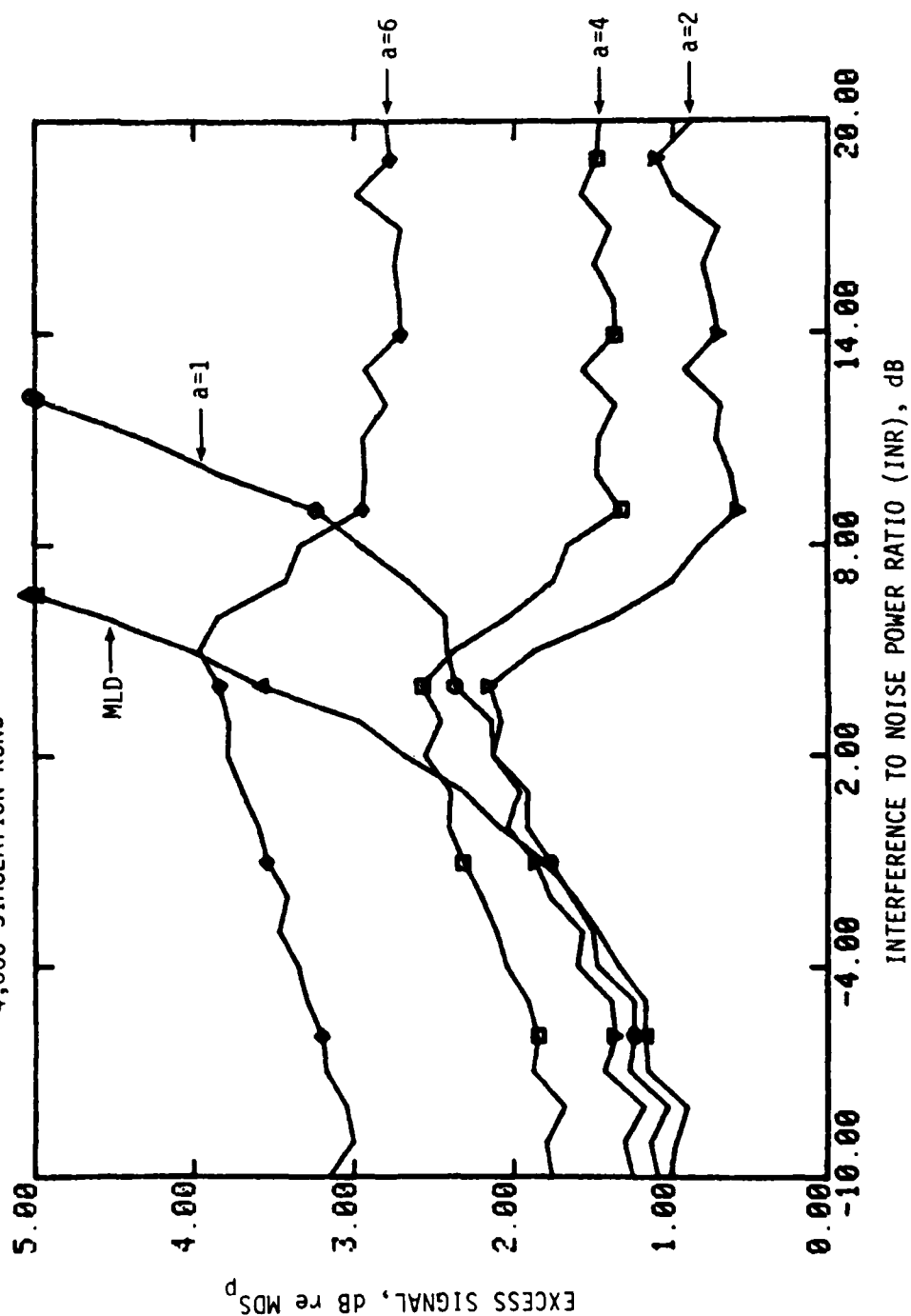


Figure 28.

# TWO-PASS CBA-CMLD PERFORMANCE IN THE PRESENCE OF INTERFERENCE

$N = 8$      $PFA = 10^{-4}$      $MDS_p = 3.01 \text{ dB}$   
 $M = 8$      $NI = 3$      $a = \text{NO. CENSORED FROM ABOVE}$   
 4,000 SIMULATION RUNS

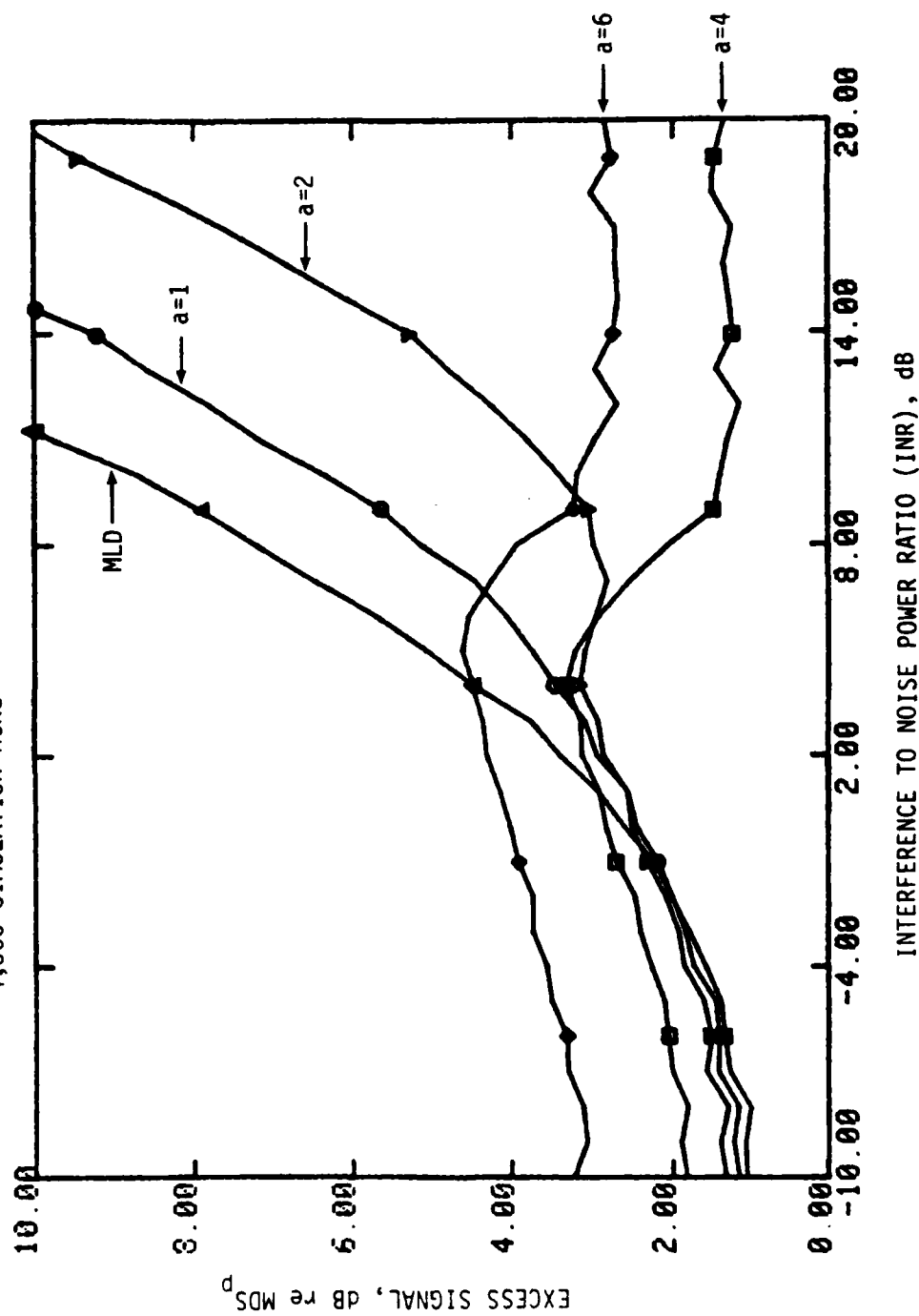


Figure 29.

Table 1. Maximum performance loss for the two-pass CBA-CMLD.

$$\text{PFA} = 10^{-4}$$

$$\text{MDS}_p = 10.90 \text{ for } N = 1$$

$$M = 8$$

$$\text{MDS}_p = 3.01 \text{ for } N = 8$$

N	a	NI	CFAR Loss (EXS) dB	Asymptotic Loss for One-Pass CBA-CMLD (EXS) dB	Maximum EXS dB	INR for Maximum EXS dB
1	1	1	3.2	4.4	4.1	10
1	2	1	3.8	4.7	4.6	10
1	2	2	3.8	6.1	5.6	10
1	4	1	5.9	6.7	6.7	6
1	4	2	5.9	7.6	7.3	10
1	4	3	5.9	8.7	8.3	10
1	6	1	13.0	13.6	13.7	18
1	6	2	13.0	14.3	14.4	18
1	6	3	13.0	15.2	15.2	18
8	1	1	0.9	2.5	1.4	0
8	2	1	1.0	2.3	1.5	2
8	2	2	1.0	4.0	2.2	4
8	4	1	1.6	2.5	2.0	2
8	4	2	1.6	3.6	2.6	4
8	4	3	1.6	4.9	3.3	4
8	6	1	2.9	3.6	3.4	5
8	6	2	2.9	4.5	4.0	5
8	6	3	2.9	5.5	4.6	5

# COMPARISON OF CBA-CMLD AND THE TWO-PASS CBA-CMLD

$N = 1$      $PFA = 10^{-4}$      $MDS_p = 10.90 \text{ dB}$   
 $M = 8$      $N1 = 1$      $a = \text{NO. CENSORED FROM ABOVE}$   
 10,000 SIMULATION RUNS

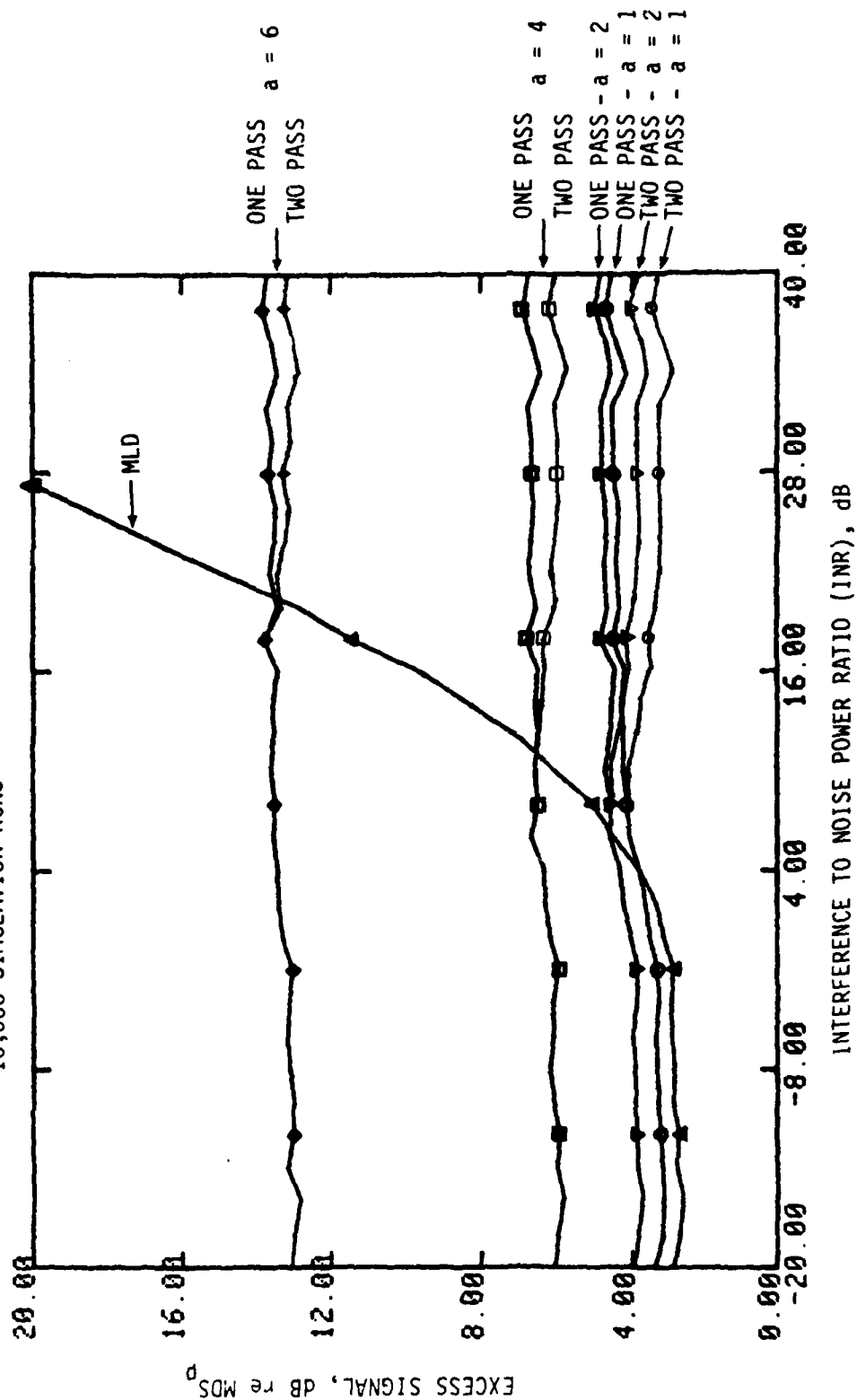


Figure 30.

# COMPARISON OF CBA-CMLD AND THE TWO-PASS CBA-CMLD

$N = 8$      $PFA = 10^{-4}$      $MDS_p = 3.01 \text{ dB}$   
 $M = 8$      $NI = 1$      $a = \text{NO. CENSORED}$   
 4,000 SIMULATION RUNS FROM ABOVE

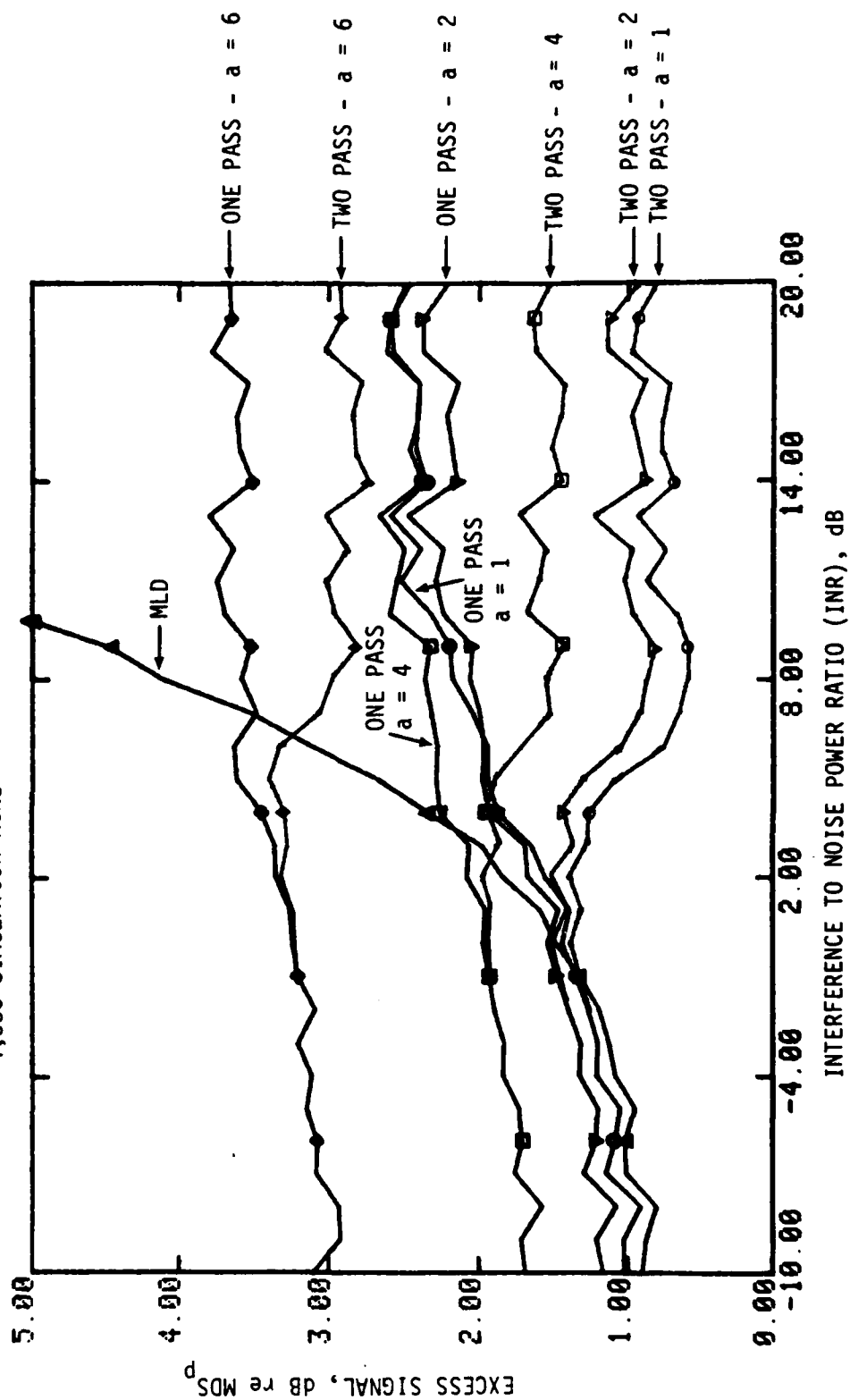


Figure 31.



## 2.5 The Censor-After-Averaging CMLD

In the <sup>c</sup>ensor-after-averaging (CAA) CMLD, the desired amount of time averaging,  $N$ , is implemented and the resulting vector of averaged power versus range is processed with the CMLD. The CAA-CMLD has two important advantages over the CBA-CMLD when a moderate to large amount of time averaging,  $N$ , is desired. First, for the CAA-CMLD only one ordering per test cell is needed per averaging epoch while  $N$  ordering operations are needed for the CBA-CMLD. Second, for the CAA-CMLD the performance loss due to presence of an interferer decreases monotonically with  $N$  while for the CBA-CMLD this loss increases monotonically with  $N$ .

The previous assumptions about the statistical distribution of the data still hold; therefore,  $S(j)$ , the average power estimate of (1) has a gamma distribution of order  $N$  (chi-square order  $2N$ ). The exact analytical expressions for the probability of detection and false-alarm have yet to be obtained for the CAA-CMLD due to the complexity of the distribution of the order statistics of a gamma distributed random process. Approximate expressions for the probability of detection and false-alarm were used in this report. These approximate expressions use an approximation to the means and covariances of the order statistics by those of a Gaussian random process when  $M$  is much less than  $N$  or the true means and covariances of the order statistics when  $M$  is near  $N$ . These means and covariances are then used to obtain the mean and equivalent number of degrees of freedom (for a gamma distribution) for the censored means which are in turn used in the probability of detection and false-alarm expressions for the MLD to give the desired approximate performance results. These approximations have been proven through simulations for a wide range of parameters when  $N$  is greater than or equal to 64.

The CAA-CMLD starts with the averaged power versus range vector,  $S(j)$ , from (1):

$$S(j) = \frac{1}{N} \sum_{k=1}^N R(j,k) . \quad (10)$$

Then, for each range cell, a local noise reference pool is defined as the  $M$ -element set:

$$U(j) = \{S(n)\}_{n=j-\frac{M}{2}, j+\frac{M}{2}}^{n \neq j} . \quad (11)$$

Then, the set  $U(j)$  is ordered in increasing power and the ordered elements of  $U$ , the order statistics, are labeled  $Y(n,j)$  where  $n$  ranging from 1 to  $M$  is the rank of the corresponding order statistic. The order statistics have the following property:

$$0 \leq Y(1,j) \leq Y(2,j) \leq \dots \leq Y(M,j) . \quad (12)$$

The biased noise power estimate,  $W(j)$ , is then formed as

$$W(j) = \frac{1}{M-a-b} \sum_{n=b+1}^{M-a} Y(n,j) , \quad (13)$$

where the  $a$  largest and  $b$  smallest averaged noise reference samples have been censored from the average. The censored mean,  $Z(j)$ , is then formed by removing the bias of  $W(j)$ ;

$$Z(j) = \frac{W(j)}{E[W]} , \quad (14)$$

where  $E[W]$ , as a function of  $N$ ,  $M$ ,  $a$  and  $b$ , is obtained analytically for  $M$  near  $N$  or through a Gaussian approximation for  $M$  much less than  $N$  (as in the results reported herein). The detection statistic is then formed as:

$$D(j) = \frac{S(j)}{Z(j)} \geq T , \quad (15)$$

and since the CMLD is a CFAR statistic, the threshold,  $T$ , is only a function of  $N$ ,  $M$ ,  $a$ ,  $b$  and the desired probability of false-alarm.

As with the CBA-CMLD (Section 2.1), the CAA-CMLD has the same special cases and limiting distributions in the presence of "large" interferers (as long as the interferer remains in the same cell over the duration,  $N$ , of the time average).

## 2.6 Performance Results for the CBA-CMLD

Figures 32 through 39 present the performance results for the CAA-CMLD in the same format as Figures 2 through 17 of Section 2.2. The results are shown for the following range of parameters: a probability of false-alarm of  $10^{-4}$ ; 512 or 1024 time averages ( $N$ ); 8, 16, 32 or 64 noise reference cells per test cell ( $M$ ); 0 to ( $M-1$ ) of the largest samples censored from the noise power estimate ( $a$ ) and 0, 1, 2 or 3 "large" interferers present in the noise reference window ( $NI$ ).

As indicated, both the CFAR loss ( $NI = 0$ ) and the loss attributable to the presence of interferers ( $NI \neq 0$ ) are small and monotonically decreasing functions of  $N$ . The advantages of the CAA-CMLD, both its computational efficiency and improved robustness, over the CBA-CMLD for moderate to large amounts of time averaging ( $N$ ) are clear from these results.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$

N = 512

▲ NI = 0  
○ NI = 1  
▼ NI = 2  
□ NI = 3

MDS<sub>P</sub> = -7.61

M = 8

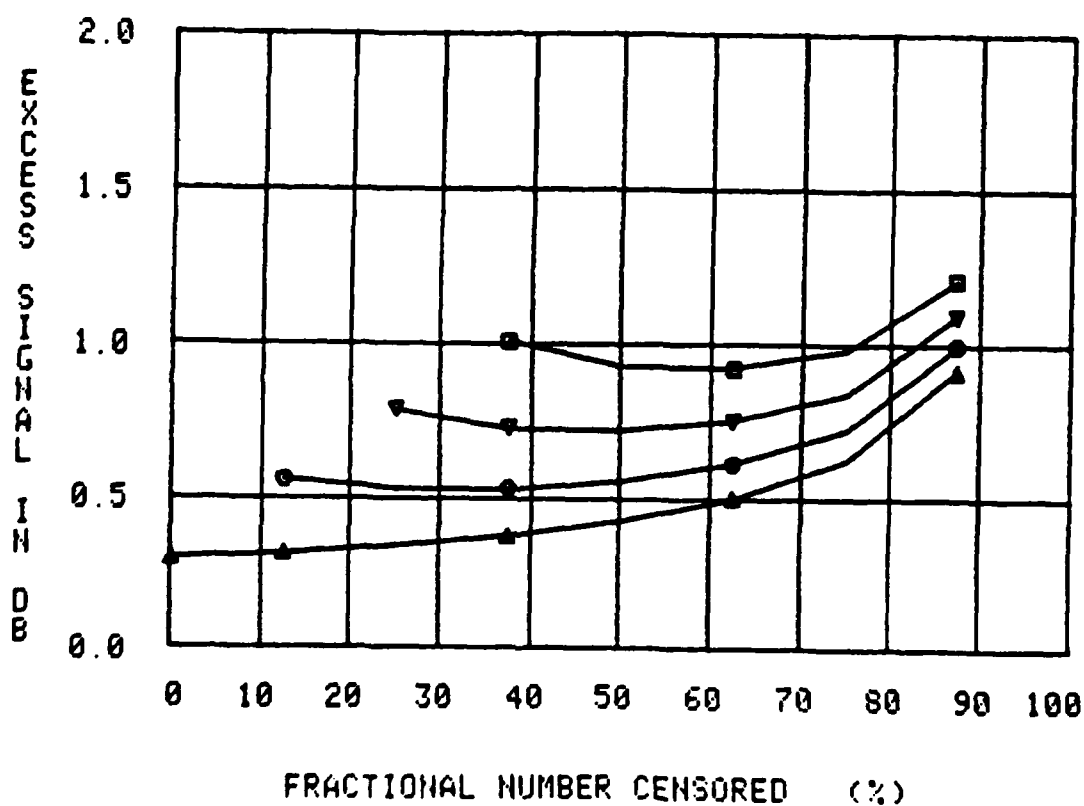


Figure 32a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$       N = 512      M = 8

○ NI = 1  
▽ NI = 2  
□ NI = 3

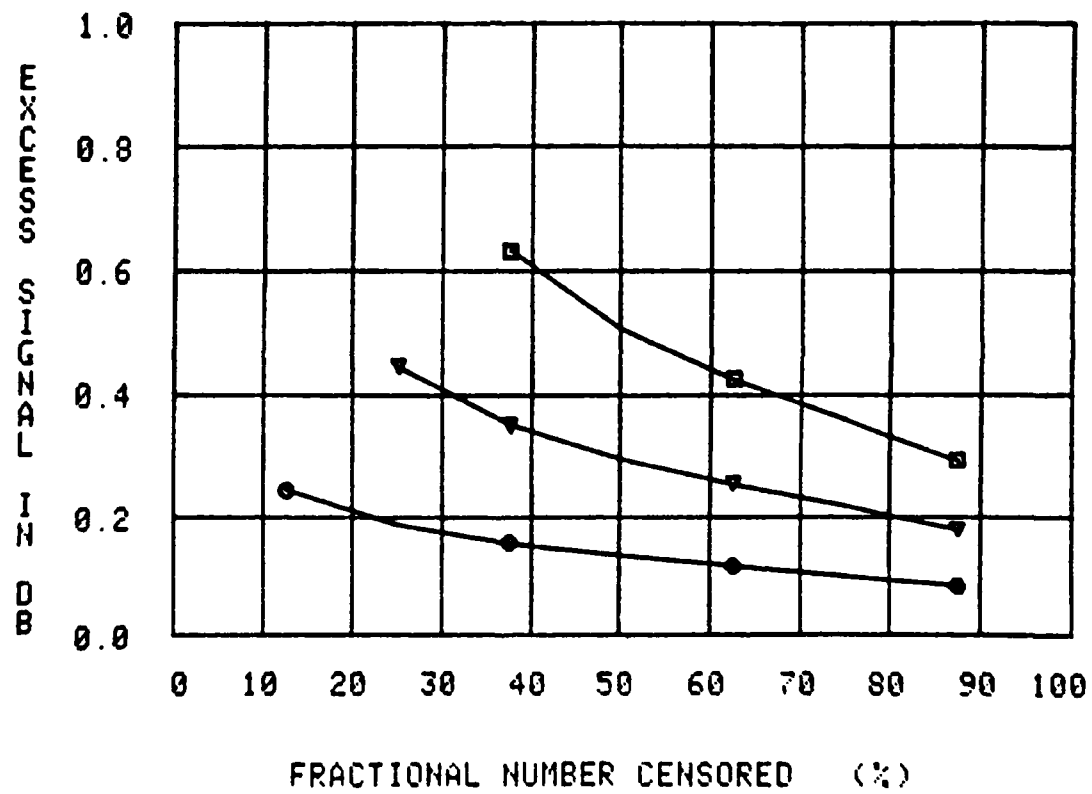


Figure 32b.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$

N = 512

MDS<sub>P</sub> = -7.61

M = 16

$\Delta$  NI = 0  
 $\circ$  NI = 1  
 $\nabla$  NI = 2  
 $\square$  NI = 3

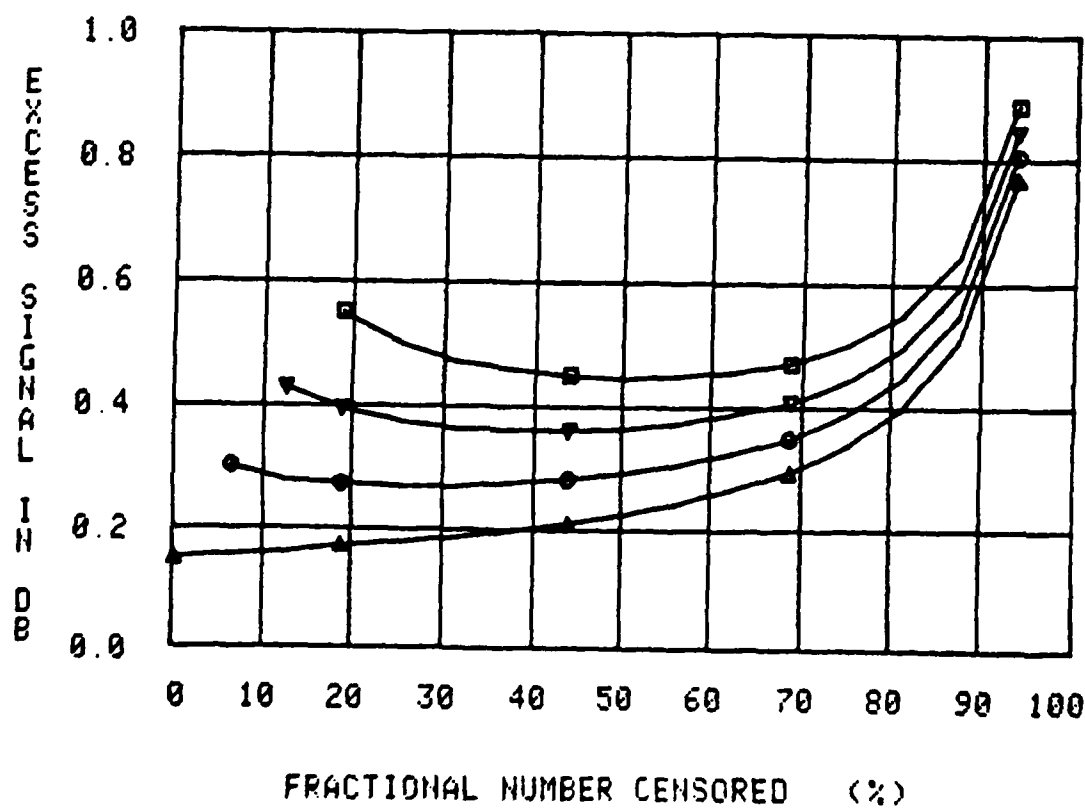


Figure 33a.

EXCESS SIGNAL NEEDED TO OBTAIN PD =  
RE MOS FOR CMLD

PFA =  $10^{-4}$       N = 512      M = 16

○ NI  
▼ NI  
□ NI

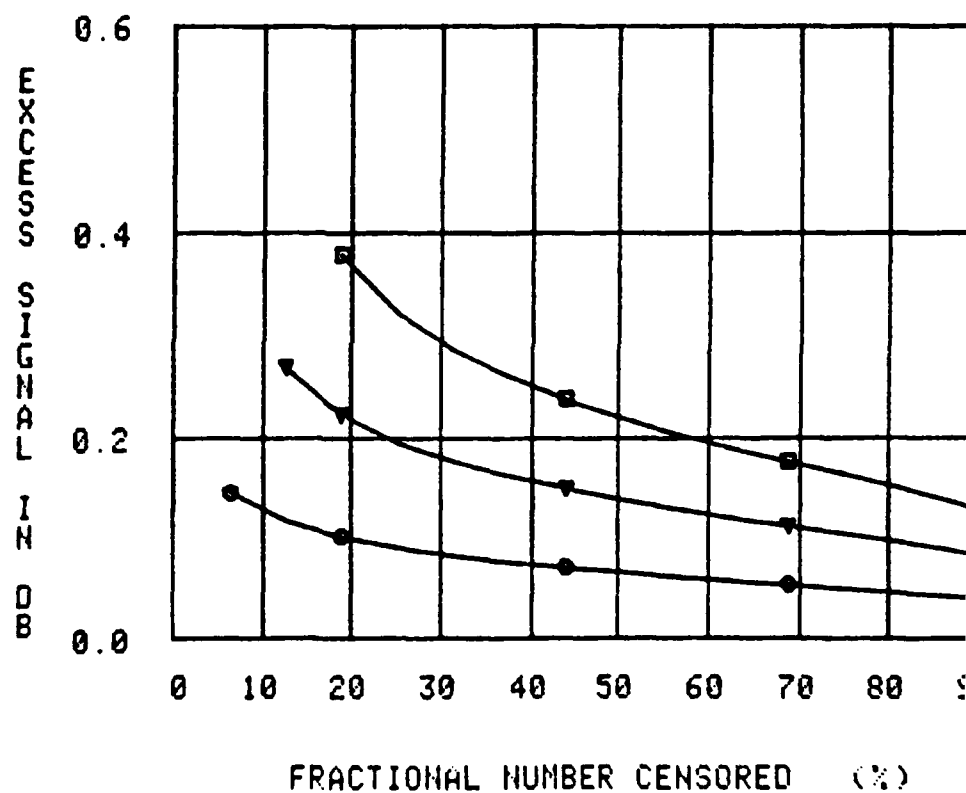


Figure 33b.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$   
MDS<sub>P</sub> = -7.61

N = 512  
M = 32

▲ NI = 0  
○ NI = 1  
▼ NI = 2  
□ NI = 3

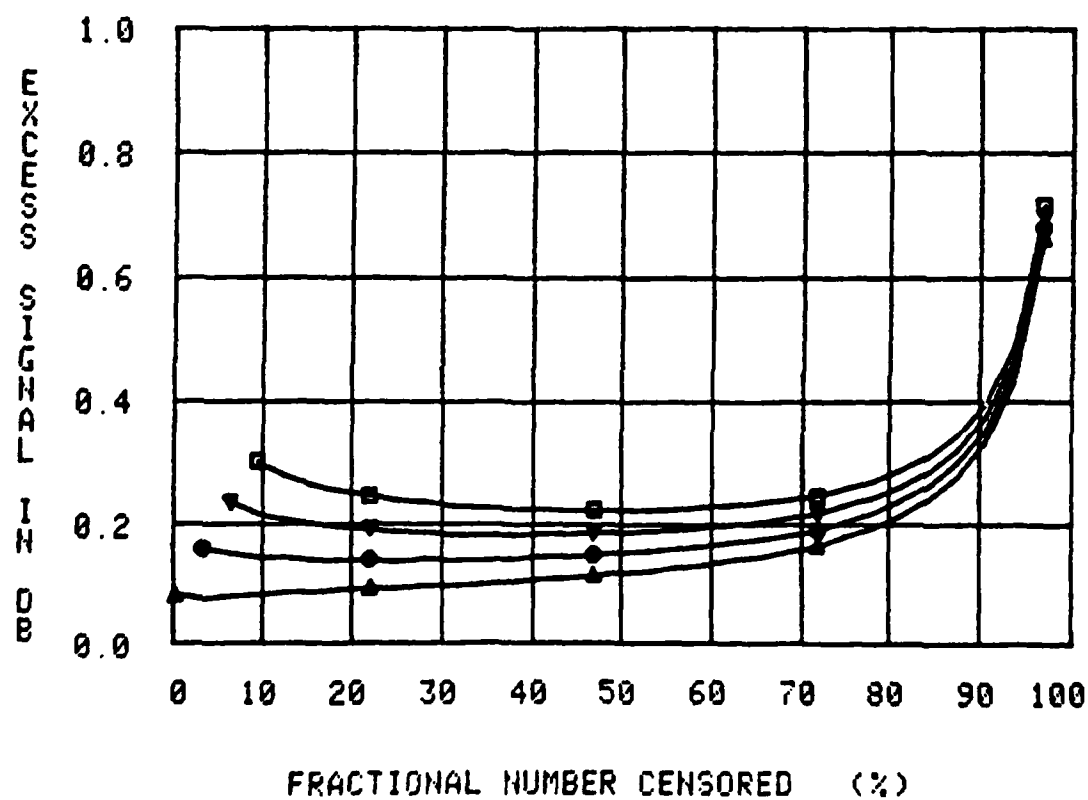


Figure 34a.



EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 512 M = 32

○ NI = 1  
▼ NI = 2  
□ NI = 3

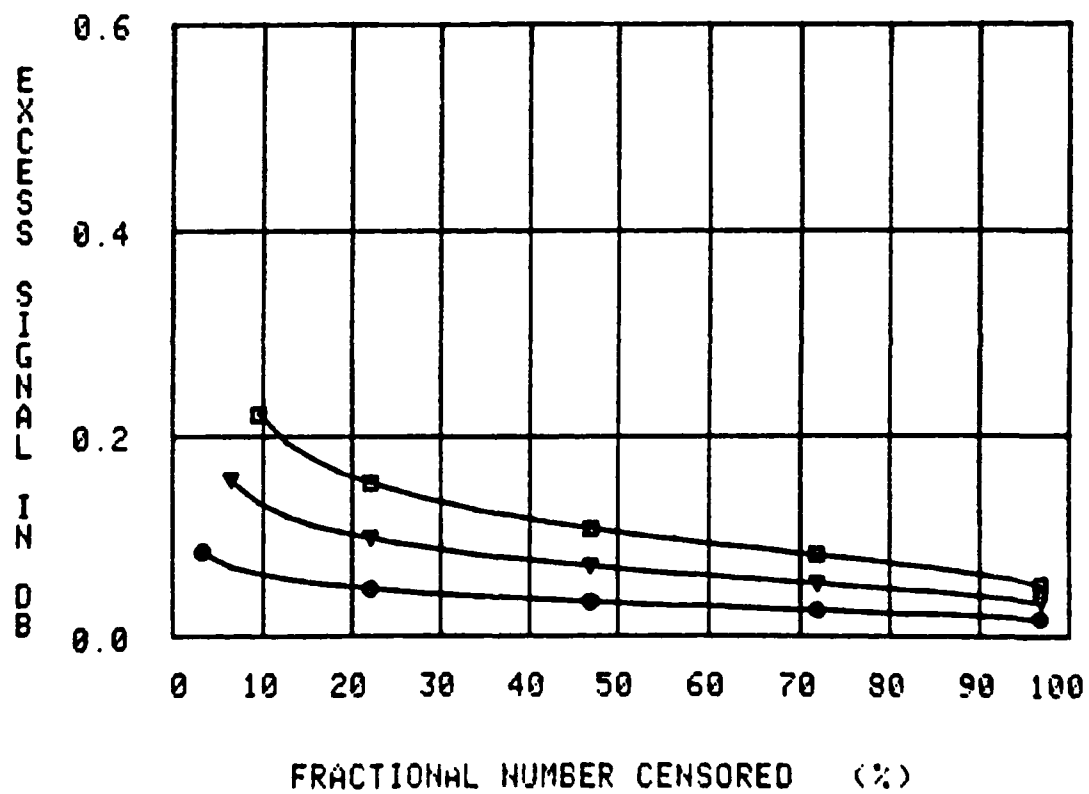


Figure 34b.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$   
MDS<sub>P</sub> = -7.61

N = 512  
M = 64

▲ NI = 0  
○ NI = 1  
▽ NI = 2  
□ NI = 3

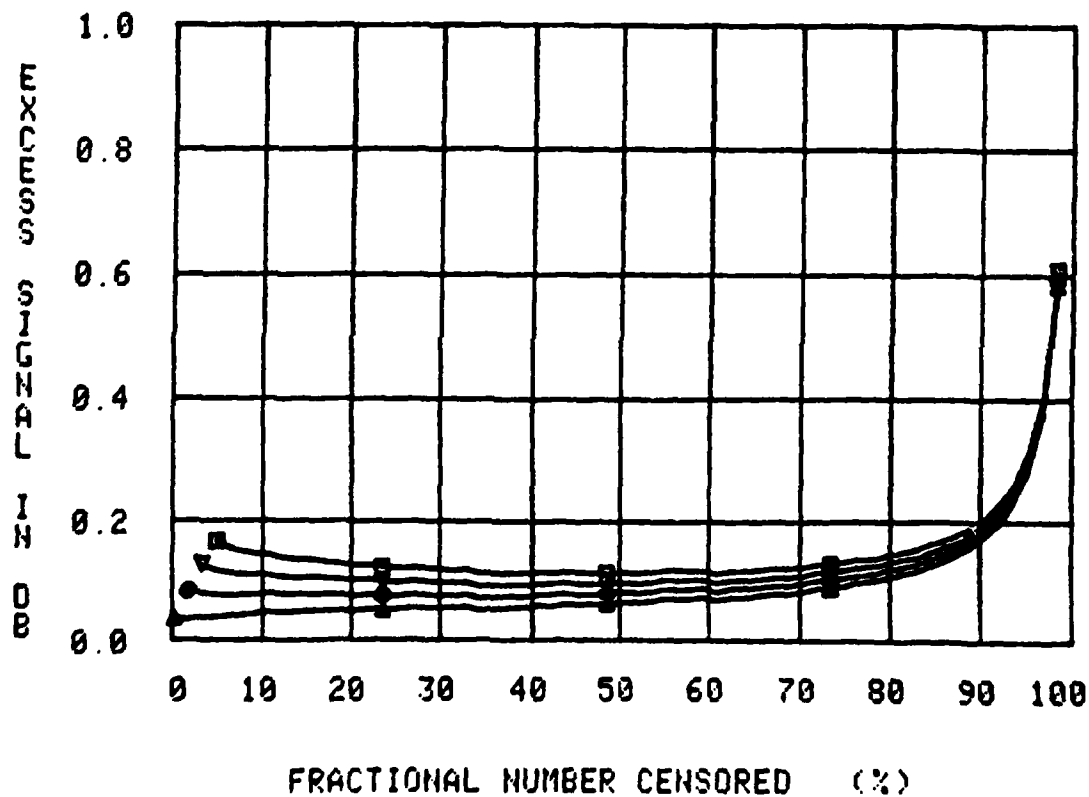


Figure 35a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 512 M = 64

○ NI = 1  
▼ NI = 2  
□ NI = 3

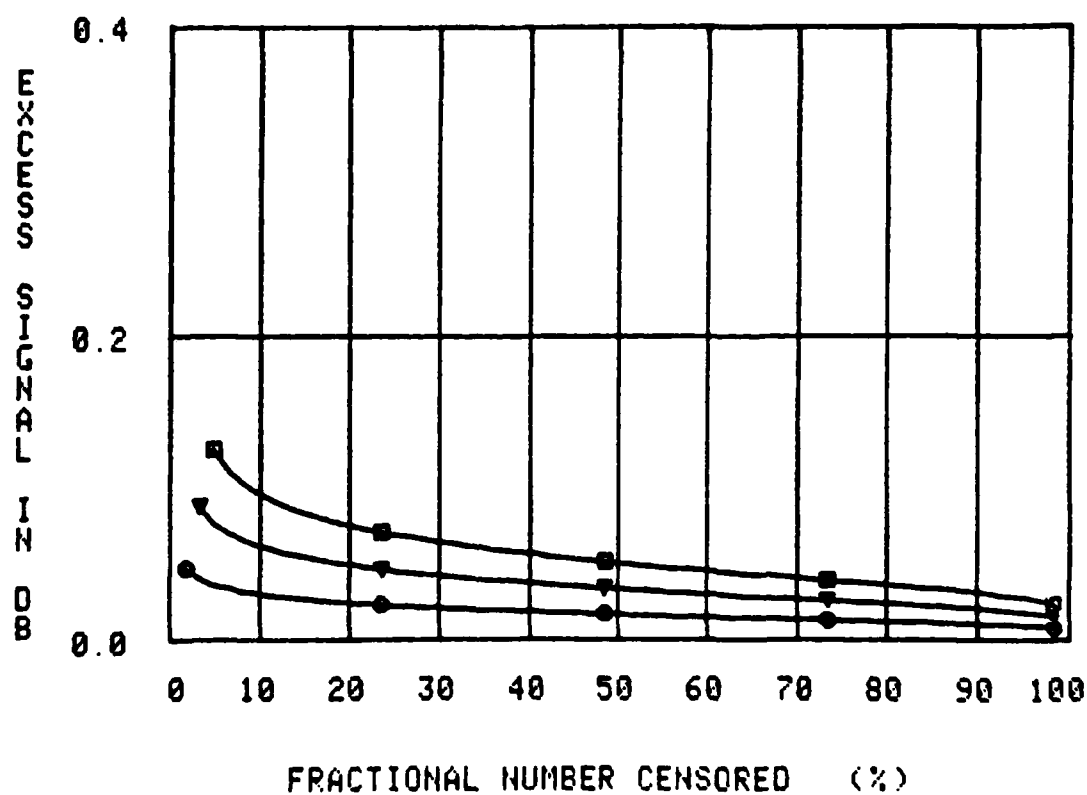


Figure 35b.

# EXCESS SIGNAL NEEDED TO OBTAIN $P_D = .5$

$PFA = 10^{-4}$

$N = 1024$

▲  $NI = 0$   
○  $NI = 1$   
▼  $NI = 2$   
□  $NI = 3$

$MDS_p = -9.19$

$M = 8$

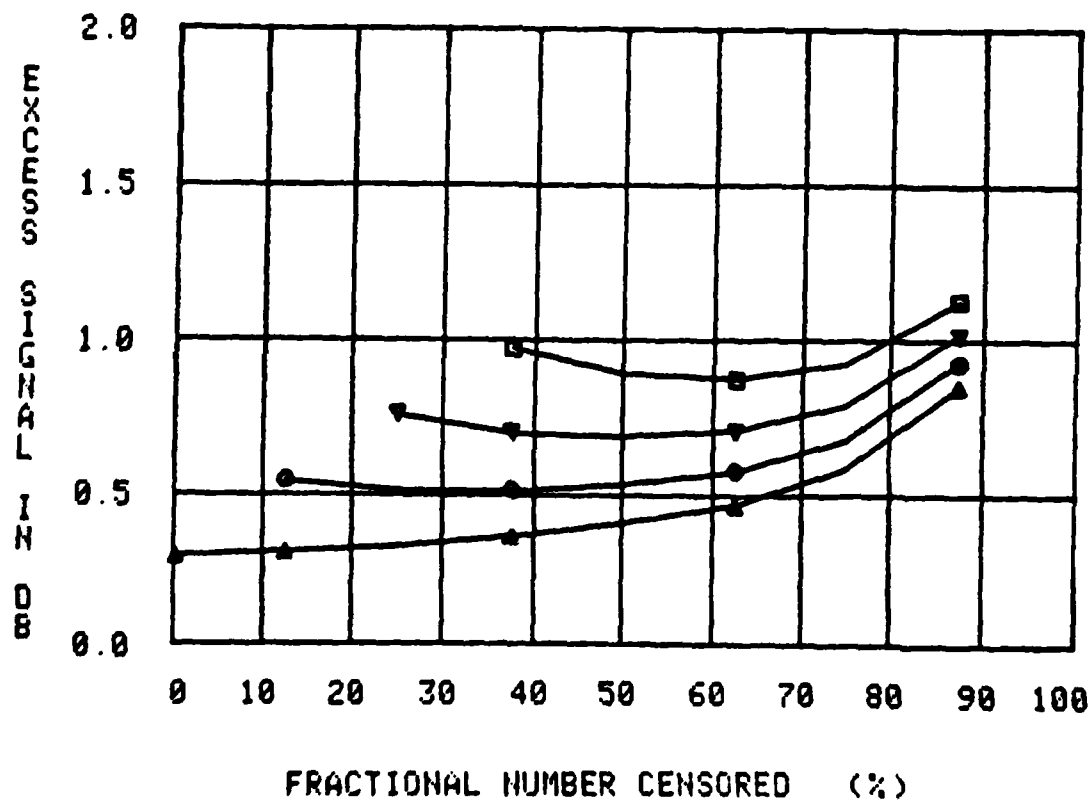


Figure 36a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 1024 M = 8

○ NI = 1  
▼ NI = 2  
□ NI = 3

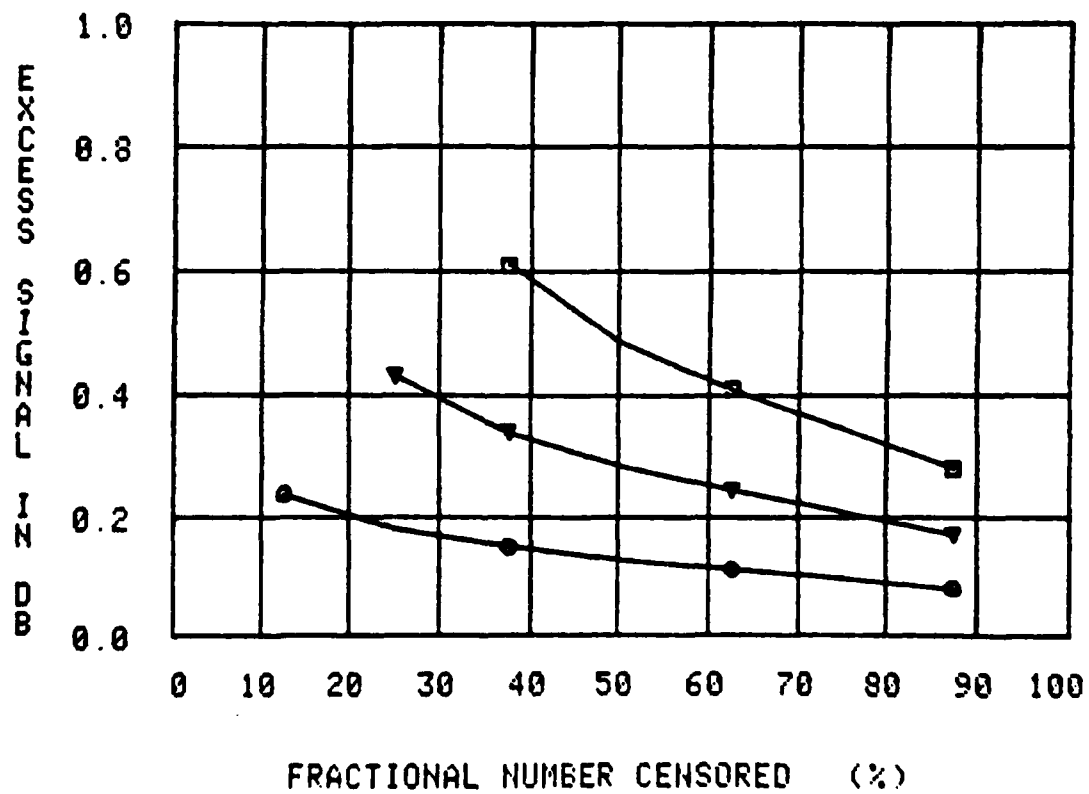


Figure 36b.

# EXCESS SIGNAL NEEDED TO OBTAIN PD = .5

PFA =  $10^{-4}$   
MDS<sub>P</sub> = -9.19

N = 1024

M = 16

▲ NI = 0  
○ NI = 1  
▼ NI = 2  
□ NI = 3

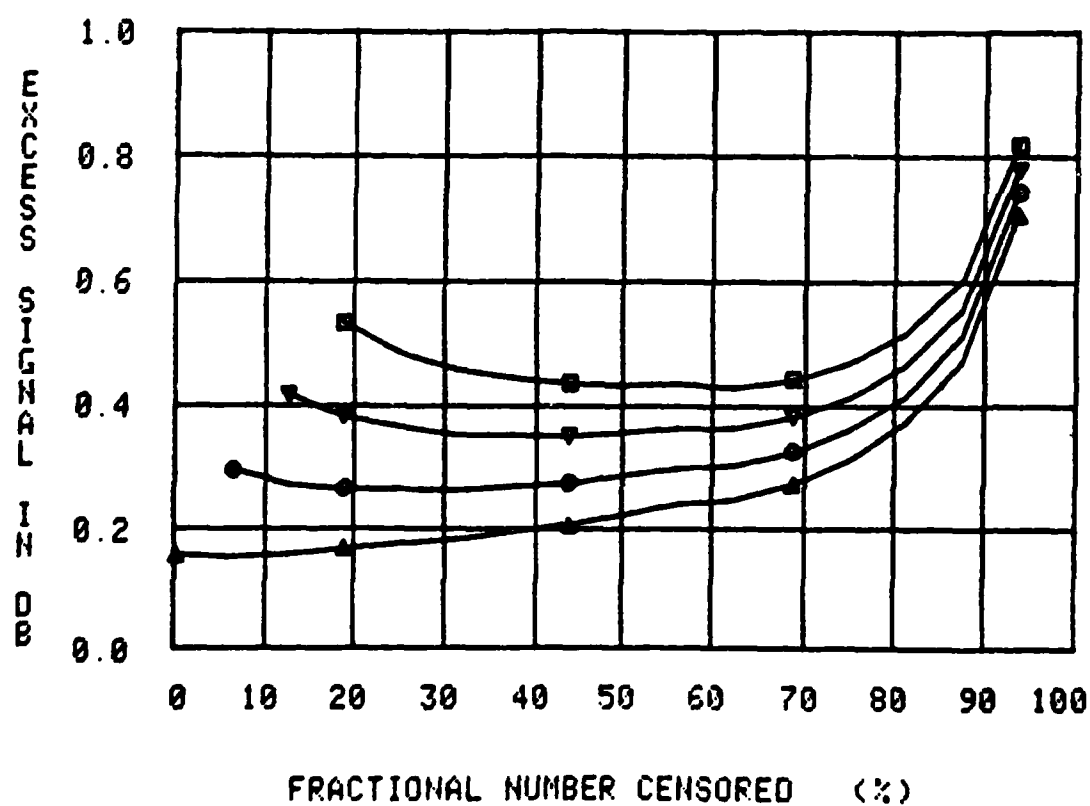


Figure 37a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLO

PFA =  $10^{-4}$

N = 1024 M = 16

○ NI = 1  
▼ NI = 2  
□ NI = 3

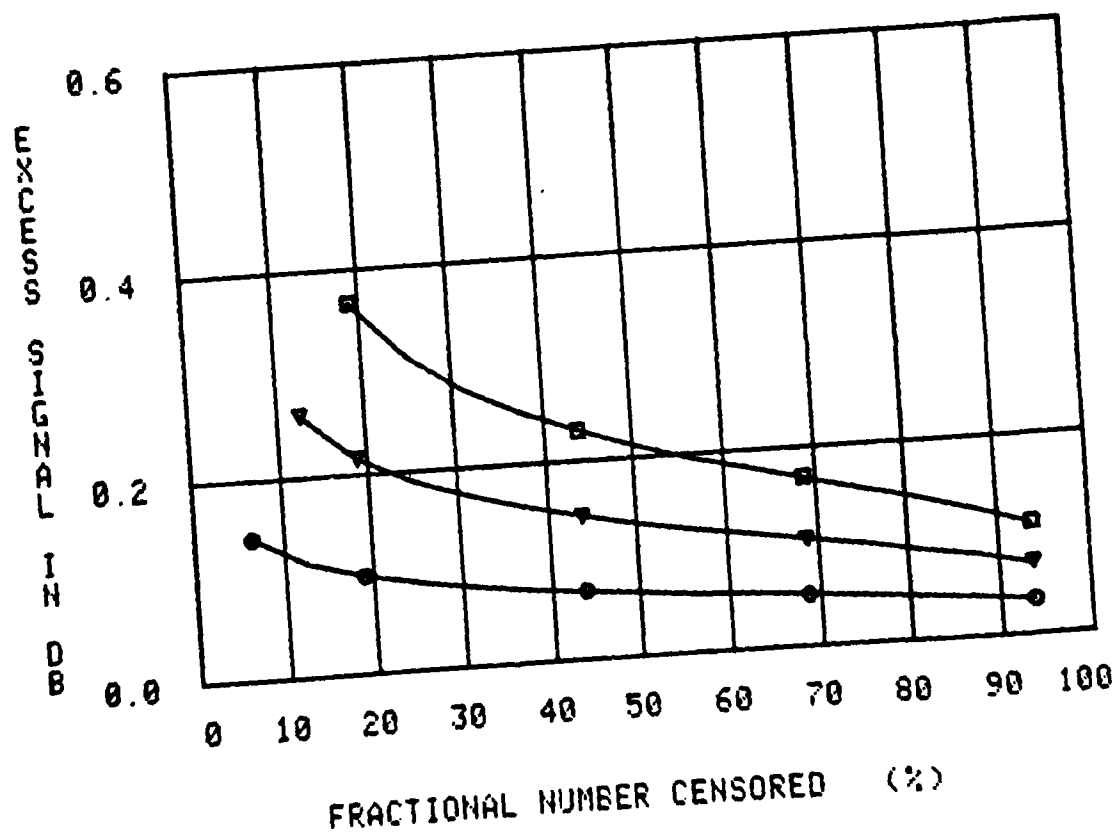


Figure 37b.

# EXCESS SIGNAL NEEDED TO OBTAIN $PD = .5$

$PFA = 10^{-4}$

$N = 1024$

$MDS_p = -9.19$

$M = 32$

$\Delta$  NI = 0  
 $\circ$  NI = 1  
 $\nabla$  NI = 2  
 $\square$  NI = 3

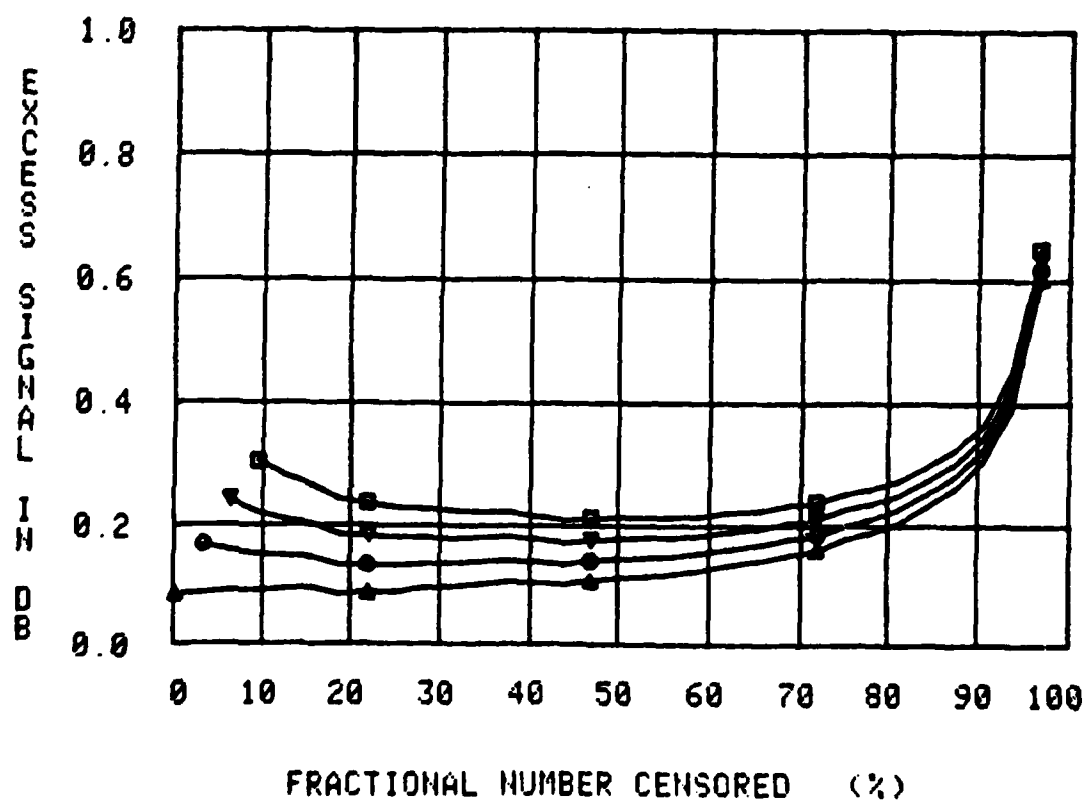


Figure 38a.



EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MDS FOR CMLD

PFA =  $10^{-4}$

N = 1024 M = 32

○ NI = 1  
▼ NI = 2  
□ NI = 3

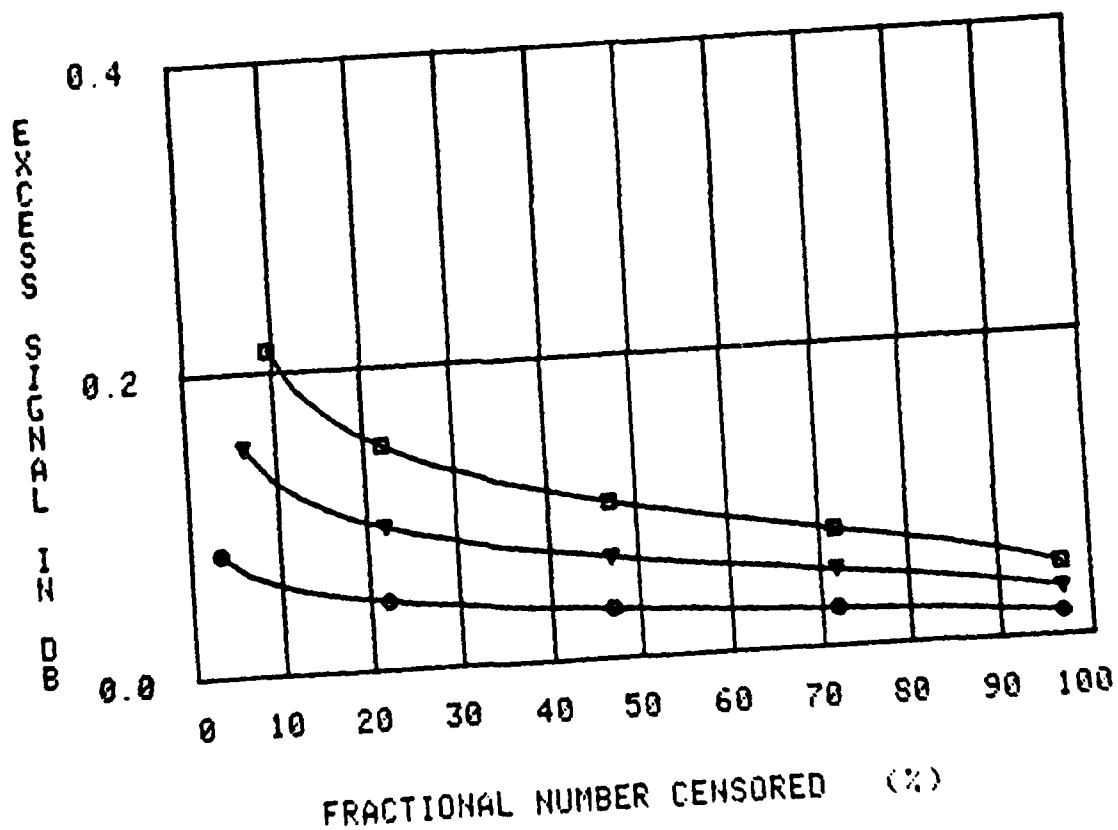


Figure 38b.

EXCESS SIGNAL NEEDED TO OBTAIN  $PD = .5$

$PFA = 10^{-4}$   
 $MDS_P = -9.19$

$N = 1024$

$M = 64$

$\Delta$  NI = 0  
 $\circ$  NI = 1  
 $\nabla$  NI = 2  
 $\square$  NI = 3

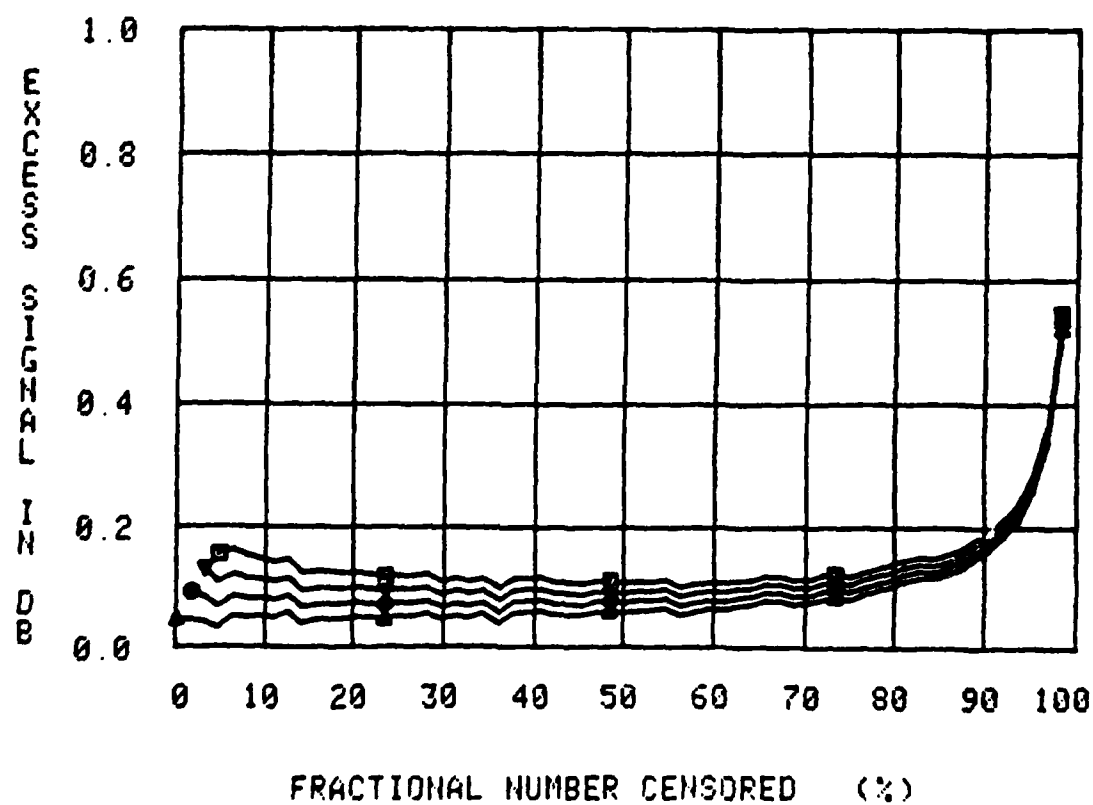


Figure 39a.

EXCESS SIGNAL NEEDED TO OBTAIN PD = .5  
RE MOS FOR CMLD

PFA =  $10^{-4}$

N = 1024 M = 64

○ NI = 1  
▼ NI = 2  
□ NI = 3

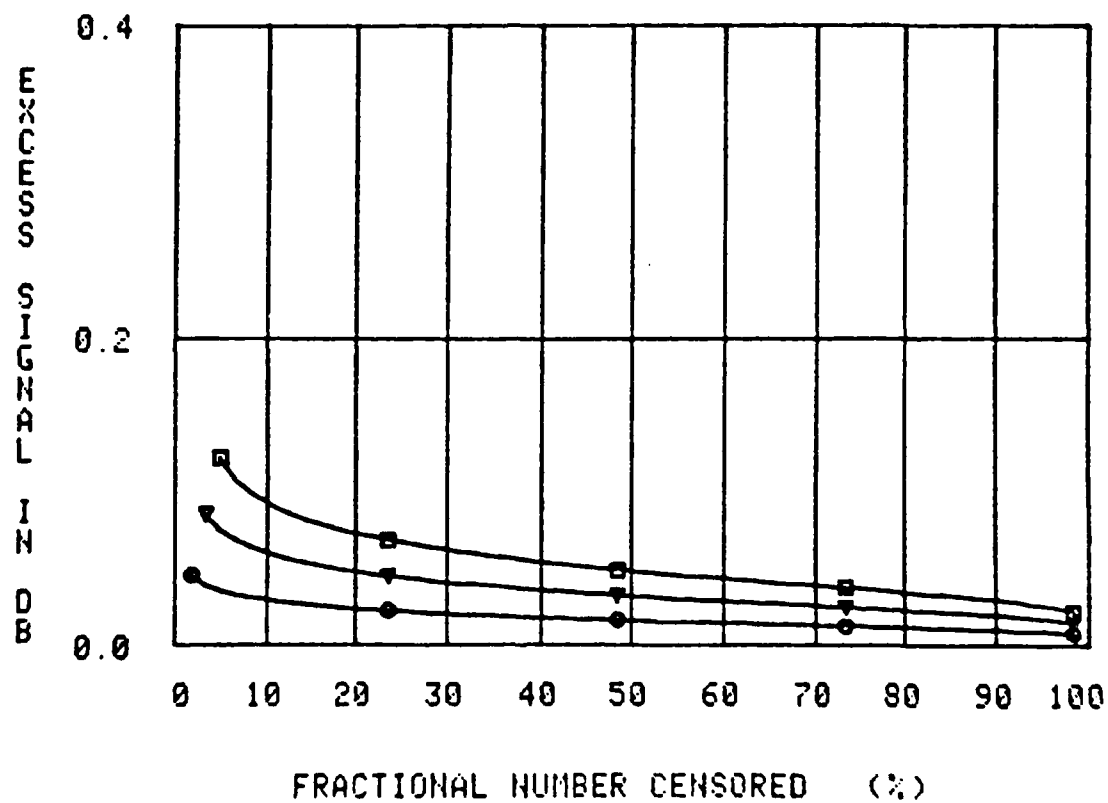


Figure 39b.

### 3.0 CONCLUSIONS

The CMLD was shown to be a statistically robust CFAR detector. The CMLD is extremely robust even when multiple, large-in-power interferers are present in the noise reference window. The two-pass CMLD provides additional robustness at a small additional computational cost. As demonstrated by the examples presented, the censoring trade-off (i.e., how much to censor) between the CFAR loss (in interference-free environments) and the robustness to multiple interferers will in general depend upon the expected density of interferers. But, as the time-bandwidth product,  $N$ , increases, the trade-off favors more and more censoring. Additionally, for moderate to large  $N$ , the CAA-CMLD provides even more remarkable robustness and a factor of  $N$  computational cost savings.

#### 4.0 REFERENCES

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